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ENERGY EFFICIENT MOTOR APPLICATION

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Motor driven processes represent a large portion of the energy consumption in the United States and, as a result, present a large opportunity for energy savings. Energy efficient motors reduce energy use and will see wider implementation as the impact of the Energy Policy Act of 1992 is felt. These motors are made possible by design and material improvements without compromising reliability, quality, or performance. One drawback is their potential for nuisance tripping due to a high inrush current at starting. Solutions do exist to this problem. Economics also play a large role in energy efficient motor application. The cost of repairing a motor or installing a new machine as well as any utility rebates determine if the efficient motor price premium is offset by energy savings. Other issues - adjustable speed drives, belts, supply voltage - affect efficiency as well. Several industry examples demonstrate the potential results. A thorough understanding of these factors show the energy efficient motor can be a good choice for most applications.

ENERGY EFFICIENT MOTOR APPLICATION

A Thesis

Presented in Partial Fulfillment of the Requirements for

the Degree Master of Science in the

Graduate School of The Ohio State University

By

Stephen R. Koenig, B.S.

****

The Ohio State University
1998

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ABSTRACT

Motor driven processes represent a large portion of the energy consumption in the United States and, as a result, present a large opportunity for energy savings. Energy efficient motors reduce energy use and will see wider implementation as the impact of the Energy Policy Act of 1992 is felt. These motors are made possible by design and material improvements without compromising reliability, quality, or performance. One drawback is their potential for nuisance tripping due to a high inrush current at starting. Solutions do exist to this problem. Economics also play a large role in energy efficient motor application. The cost of repairing a motor or installing a new machine as well as any utility rebates determine if the efficient motor price premium is offset by energy savings. Other issues - adjustable speed drives, belts, supply voltage - affect efficiency as well. Several industry examples demonstrate the potential results. A thorough understanding of these factors show the energy efficient motor can be a good choice for most applications.

Dedicated to my parents

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CHAPTER 1

INTRODUCTION

Estimates vary as to what percentage of the total energy used in the U.S. is consumed by motor-driven systems. As early as 1976, A.D. Little completed the study, "A Technical Economical and Policy Analysis of Electric Motor Equipment," for the Federal Energy Administration. The report stated 64 percent of the nation's consumed energy is done so by electric motor systems [Bonnett 1980]. A more recent 1993 citation gave 53 percent as the amount of electricity consumed by motors in the U.S. [Rosenberg 1997]. Also, the Department of Energy found motor driven equipment accounted for 69 percent of all electricity consumption by U.S. industries in 1993 [McCoy 1997]. In any case, electric motor driven systems by far are the largest consumers of electricity in the United States. As a result, they present the largest opportunity for energy savings.

A breakdown of the different ways electric motors are used was developed by the company XENERGY from several different sources and is shown below [Rosenberg 1997].

Sector/End Use	% of Total Motor kWh	% of Sector Motor kWh
Residential	**23**	
Heating	2.5	11
Cooling	7.8	34
Appliances	12.7	55
Commercial	**20**	
HVAC	16.3	82
Refrigeration	4.5	18
Utilities(pumps and fans)	**13**	
Industrial	**44**	
Pumps, Fans, Compressors	18.0	41
Materials Handling	12.0	27
Materials Processing	14.1	32

Table 1.1: Distribution of Motor Drive Energy.

Residential users only account for 23 percent of total motor energy consumption while industrial type users (manufacturing, utilities, commercial activity) account for the other 77 percent.

To exploit this potential, companies have been designing energy efficient motors (EEM) for decades. Use of these products lower energy consumption for the owner and as a result, decrease monetary costs. This is important as power costs (in 1994) were already over $0.07/kWhr in most areas and economists predict by the year 2000 the cost could reach $0.18/kWhr [Hirzel 1994]. The EEM also has the potential to reign in future electric generation requirements. However, with the advent of deregulation, the potential economic benefit for utility companies is not so clear. The reduction of generation requirements, on the other hand, does reduce potential emissions from utility plants [Nailen 1997]. This can reduce pressure from environmental lobbies who might otherwise achieve their goals through legislation. Additionally, the effort to increase efficiency itself has produced a machine with other benefits such as greater reliability and life expectancy [Bonnett 1997].

While the advantages are many, some technical problems with EEMs still remain. One oft encountered problem in EEM application is the increased peak inrush current at motor start. If not properly accounted for, this can result in nuisance tripping of the motor protective devices. Energy efficient designs produce motors with lower than standard full-load currents for a given horsepower rating [Bartheld and Farag 1985]. This changes the ratio of locked rotor current to full load current which is used to determine the trip setting for protective devices. Additionally, increased peak inrush current results from improved efficiency increasing the motor's X/R ratio [Hartman 1985]. The winding resistances are reduced and the X/R ratio increases, leading to a larger peak inrush current. Another possibility for increased inrush current (and nuisance tripping) is the general increase in starting torque and inrush current over the last 30 years [Bonnett 1997]. These concerns

require careful attention to the actual motor application and, as shown later, can be overcome with the proper use of inverse time circuit breakers.

The industry's response to the motor efficiency challenge started in 1962 as improvements were made to the old "U" frame motor. The U-frame was the original standard adopted by the National Electrical Manufacturers Association (NEMA) in 1953. It was a rugged, efficient motor and over-designed to ensure it could meet performance specifications. Design capabilities and computer simulation were not what they are today and so any assumption was made on the side of over-caution. These design contingencies also had to overcome deviations in material quality, manufacturing imperfections, and a quality control system which could let a significant number of flawed motors into commercial use [Palko 1982].

To offset this overdesign and the accompanying costs, the T-frame motor was introduced in 1962-1963. This line made use of improvements in design techniques, computer simulation, and material and manufacturing quality control to provide a motor which could do the job of a similar U-frame motor at lower cost. However, since fewer windings were used (to reduce cost) the motor ran hotter and so the efficiency and power factor were lower [Bonnett 1994b]. This solution was satisfactory as long as the energy costs stayed low and did not become large relative to the motor cost. However, as energy costs inched upward in the 1970's, the expensive-to-operate T-frames became less desirable.

Reversion to the old U-frame was not a desirable solution either. The smaller and lighter T-frame had seen a wide application and in many cases it would not be possible to retrofit with the larger and heavier U-frame. So in 1974 the first line of energy efficient motors came out which could take the place of a T-frame. In 1977, NEMA defined motor

efficiency guidelines for standard efficiency motors. This was updated in 1987 with standards for energy efficiency motors, and again in 1990. Eventually, the energy efficient motor standards were passed into law under the Energy Policy Act of 1992 for newly manufactured motors.

The Energy Policy Act (EPACT) of 1992 was signed into law by President George Bush on October 24, 1992. It mandated new efficiency standards, testing, and labeling requirements for NEMA motors manufactured after the phase-in date. Key features of this act as it related to induction machines were the adoption of the already existing nominal efficiency standards for energy efficient motors, the existing NEMA labeling practice, and the established IEEE standard for testing of electric motors - IEEE 112 Method B [Bonnett 1994a]. In essence, all new motors after the phase-in period would have to be energy-efficient. The following summarizes the primary features of the EPACT legislation [Kline 1997]:

- Products covered are 1-200 hp 2/4/6 pole horizontal general purpose polyphase motors. (Definite and special purpose motors as defined by NEMA are not covered by the Act).

- Requires IEEE 112 Method B/National Voluntary Lab Accreditation Program modified test procedures.

- All nameplates will be marked with a DOE energy mark including a manufacturer's specific compliance number issued by the DOE. Each nameplate will include the NEMA nominal efficiency.

- All regulated products produced after October 24, 1997 must comply with the regulations (phase-in period).

- All state and local efficiency regulations are superseded by EPACT 92.

This legislation has ensured end-users will encounter energy efficient motors in one form or another. As a new baseline for all manufactured motors, equipment developers will continue working to improve efficiency and develop the "next generation" of EEMs. The EPACT legislation could also have the added effect of reducing utility rebates for installing energy efficient units as most users will have no choice but to install EEMs when beginning new operations. In all cases, the motor user/owner needs to understand how the EEM is constructed and tested in order to apply it in a cost efficient manner.

By a thorough literature review, this work seeks to explain the EEM's value when properly applied. It is possible for motor users to shy away from energy efficient units due to concerns over its lifespan or the effect on motor controllers and circuit interrupters. Caution also arises over the motor's actual efficiency and what the real cost benefits are. By a thorough understanding of efficiency measurement and motor construction, as well as the monetary aspects of the decision process, I hope to convince the reader the EEM is a good choice for most situations.

CHAPTER 2

DEFINING EFFICIENCY

Correct EEM application begins with the understanding of how the unit's efficiency is defined. The basic expression for efficiency is straightforward but discretion must be applied when looking at numbers for different machines. The various testing methods available are differentiated by how they interpret this definition. The standard highlighted in the EPACT legislation has become the accepted method in the United States as it was originally promulgated by NEMA. The first thing to look at then are the different interpretations of efficiency, and the second are the standards resulting from NEMA's application.

2.1. Efficiency - Calculations and Measurement

Efficiency as applied to motors begins with the ratio of output power to input power where input power equals output power plus machine losses [Bonnett 1980], [Andreas 1992]:

$$E = [W_{out}/(W_{out} + W_{loss})] * 100 \tag{2.1}$$

The losses can be broken out into:

W_s: stator winding $I_1{}^2R_1$ loss
W_r: rotor winding $I_2{}^2R_2$ loss
W_c: core loss (hysteresis and eddy current losses)

FW: friction and windage losses
W_L: stray load losses.

Core loss and friction and windage losses are no load losses which occur in any motor. Friction loss results from interaction at the motor bearings. Windage loss comes about from the motor cooling fan and air drag on the rotor. The core loss components are hysteresis and eddy current losses which energize the motor magnetic circuit. Both of these occur whether or not the motor is producing any work on the output shaft. They account for about 30 percent of the total losses in a motor. The remaining 70 percent come from load losses when the motor is producing work. The stator and rotor losses result from the resistance of the materials used in the stator, rotor bars, and motor magnetic steel circuit. These can be minimized by material selection. Harmonic and circulating current losses in the windings and magnetic steel cause stray load losses which can be reduced through design and manufacturing process control [Hirzel 1992]. These losses are, of course, the focus of design and material improvements to create energy efficient motors.

It is important to remember motor efficiency does not determine the efficiency for the entire process. According to 1994 Department of Energy figures, only 18 percent of possible sources of energy conservation in electrical equipment use will come from motors. The breakdown is shown as [Nailen 1997]:

Area	Percentage of Potential Energy Savings within a Process
Motor	18
Electrical Distribution	8
Better Control (ASDs)	41
Process Optimization	33

Motors use up little energy as they convert most of it into useful work. The losses associated with most motor driven equipment appear largely outside the motor itself [Nailen 1992]. In a typical motor driven pump system, a much greater proportion of losses occur in the combined total of: pumps and valves, piping, the transformer, and the power distribution system. It then becomes important to not stop the efficiency evaluation at the motor but also examine these other processes. As motor efficiencies increase, losses will have to be squeezed out of some of these other segments of the process. Alternatives to exploit these possibilities are examined in Chapter 7. While the definition outlined in (2.1) seems self-explanatory, there are different ways to interprete the variables, namely the losses.

There are several different recognized methods of testing motors. The most common are [Nadel 1991]:

CSA C390	Canadian
NEMA MG-1	United States (IEEE 112-B)
IEC 34.2	International Electrotechnical Commission
JEC-37	Japanese.

IEEE 112 Method B is the preferred standard in the United States. A dynamometer loads the motor at full load and the power is directly measured. The losses are segregated (evaluated individually) and summed to arrive at the total motor loss [Jordan 1994]. Different methods exist for motors too large to be connected to a dynamometer. A brief comparison shows the impact different testing methods have on a single motor's horsepower and efficiency [Bonnett 1994a]:

	NEMA MG-1	JEC-37	IEC 34.2
hp	71.3	70.0	73.4
eff (%)	90.0	93.1	92.7

Additionally [Nadel 1991],

Standard	Full Load Efficiency At 7.5 hp	At 20 hp
CSA C390	80.3	86.9
NEMA MG-1	80.3	86.9
IEC 34.2	82.3	89.4
JEC-37	85.0	90.4

From this sampling of motor efficiencies, CSA and NEMA both have very similar results. They both account for stray load losses in addition to measurable losses. IEC is not as conservative, allowing a tolerance in measurement readings and assuming a stray load loss fixed at 0.5% of full load power. The JEC standard is even more optimistic, ignoring stray load losses altogether.

Accounting for stray load losses is a result of measuring motor efficiency directly, as opposed to indirectly vis-a-vis IEC and JEC. Attaching a dynamometer to the motor provides simultaneous measurements of input and output power. The dynamometer measures torque or power of the driving test motor. A dc generator, whose shaft is connected to the motor under test, absorbs the power from the drive motor [Mecker July 1994]. This, along with other information gathered by measuring the phase and line currents, voltages, and other pertinent data, provide what is needed to determine the motor losses. The input power is measured at the motor terminals and then efficiency, output power divided by input power, is easily determined.

A comparison of IEC 34.2 and IEEE 112-B [Bartheld and Kline 1997] highlights some of the features of direct measurement. For instance, IEC assumes an operating temperature for I^2R losses whereas IEEE uses the actual temperature measurements. This leads to a more accurate determination of core, rotor I^2R, and stator I^2R losses. In addition, it also improves the stray load loss estimate. IEC fixes stray load losses at 0.5 percent

of the rated input power for the motor. IEEE on the other hand, calculates the stray load loss separately for each load point, using the segregated losses calculated previously.

The friction and windage loss is determined by running the motor uncoupled with a variable voltage supply. Input-output tests determine the I^2R (stator, rotor) and core losses. Now the stray load loss can be calculated by subtracting the measured loss from the apparent total loss (input power minus output power). This is done for several load points and then plotted as stray load loss vs. torque squared. A least squares fit provides an adjusted stray load loss over the entire range of load points and this is used with the final loss values (corrected to a standardized temperature) to determine the final motor efficiency value as a function of load [Cummings 1997].

2.2. NEMA Standards

Two efficiencies, nominal and minimum, are of concern for motor selection.

The first, nominal efficiency, is defined by NEMA as "... shall be not greater than the average efficiency of a large population of motors of the same design." [NEMA 1993]. Variations in materials, manufacturing processes, and tests result in efficiency fluctuations for a given motor design. Therefore, it is more convenient to define a band of motor efficiencies for a given horsepower. The nominal represents the maximum efficiency at a given level and the minimum gives the lower limit at that horsepower.

NEMA defines minimum efficiency in Table 12-8 as the efficiency resulting from losses no more than 20% greater than for the nominal efficiency [NEMA MG1-1993, section 12, p. 19]. This is the guaranteed efficiency which a manufacturer must meet to have their device classified at a certain efficiency level. The nominal efficiency is used to evaluate a group of motor's performance in service, or the "average" motor. This provides a

basis for the consumer to compare the same horsepower motor from different manufacturers. The minimum acceptable level of efficiency provides a lower boundary for the efficiency range at a certain horsepower. This is the value to use when selecting an individual motor [Mecker July 1994].

Once the testing methods, labeling requirements, and efficiency level are established, the next step is to actually divide the efficiency spectrum into different levels which energy efficient motors must meet or exceed. The original values were adopted in 1989 and the final values published in 1993 [Cummings 1997], [NEMA 1993]. The following table shows the resulting breakdown [NEMA MG 1-1993, Table 12-9]. Note the minimum and nominal efficiency at each horsepower level creates an "efficiency band" to allow for variations in testing and measurement. The minimum level provides a firm number to make it easier to compare individual units.

Hp	Two Pole		Four Pole		Six Pole		Eight Pole	
	Nominal Efficiency	Minimum Efficiency	Nominal Efficiency	Minimum Efficiency	Nominal Efficiency	Minimum Efficiency	Nominal Efficiency	Minimum Efficiency
1.0	-------	--------	82.5	80.0	77.0	74.0	72.0	68.0
1.5	80.0	77.0	82.5	80.0	82.5	80.0	75.5	72.0
2.0	82.5	80.0	82.5	80.0	94.0	81.5	85.5	82.5
3.0	82.5	80.0	86.5	84.0	85.5	82.5	86.5	84.0
5.0	85.5	82.5	86.5	84.0	86.5	84.0	87.5	85.5
7.5	85.5	82.5	88.5	86.5	88.5	86.5	88.5	86.5
10.0	87.5	85.5	88.5	86.5	90.2	88.5	89.5	87.5
15.0	89.5	87.5	90.2	88.5	89.5	87.5	89.5	87.5
20.0	90.2	88.5	91.0	89.5	90.2	88.5	90.2	88.5
25.0	91.0	89.5	91.7	90.2	91.0	89.5	90.2	88.5
30.0	91.0	89.5	91.7	90.2	91.7	90.2	91.0	89.5
40.0	91.7	90.2	92.4	91.0	91.7	90.2	90.2	88.5
50.0	91.7	90.2	92.4	91.0	91.7	90.2	91.7	90.2
60.0	93.0	91.7	93.0	91.7	92.4	91.0	92.4	91.0
75.0	93.0	91.7	93.6	92.4	93.0	91.7	93.6	92.4
100.0	93.0	91.7	93.6	92.4	93.6	92.4	93.6	92.4
125.0	93.0	91.7	93.6	92.4	93.6	92.4	93.6	92.4
150.0	93.6	92.4	94.1	93.0	93.6	92.4	93.6	92.4
200.0	93.6	92.4	94.1	93.0	94.1	93.0	93.6	92.4

Table 2.1: Full Load Efficiencies of Energy Efficient Motors - Open Motors.

Hp	Two Pole		Four Pole		Six Pole		Eight Pole	
	Nominal Efficiency	Minimum Efficiency	Nominal Efficiency	Minimum Efficiency	Nominal Efficiency	Minimum Efficiency	Nominal Efficiency	Minimum Efficiency
1.0	-------	--------	80.0	77.0	75.5	72.0	72.0	68.0
1.5	78.5	75.5	81.5	78.5	82.5	80.0	75.5	72.0
2.0	81.5	78.5	82.5	80.0	82.5	80.0	82.5	80.0
3.0	82.5	80.0	84.0	81.5	84.0	81.5	81.5	78.5
5.0	85.5	82.5	85.5	82.5	85.5	82.5	84.0	81.5
7.5	85.5	82.5	87.5	85.5	87.5	85.5	85.5	82.5
10.0	87.5	85.5	87.5	85.5	87.5	85.5	87.5	85.5
15.0	87.5	85.5	88.5	86.5	89.5	87.5	88.5	86.5
20.0	88.5	86.5	90.2	88.5	89.5	87.5	89.5	87.5
25.0	89.5	87.5	91.0	89.5	90.2	88.5	89.5	87.5
30.0	89.5	87.5	91.0	89.5	91.0	89.5	90.2	88.5
40.0	90.2	88.5	91.7	90.2	91.7	90.2	90.2	88.5
50.0	90.2	88.5	92.4	91.0	91.7	90.2	91.0	89.5
60.0	91.7	90.2	93.0	91.7	91.7	90.2	91.7	90.2
75.0	92.4	91.0	93.0	91.7	93.0	91.7	93.0	91.7
100.0	93.0	91.7	93.6	92.4	93.0	91.7	93.0	91.7
125.0	93.0	91.7	93.6	92.4	93.0	91.7	93.6	92.4
150.0	93.0	91.7	94.1	93.0	94.1	93.0	93.6	92.4
200.0	94.1	93.0	94.5	93.6	94.1	93.0	94.1	93.0

Table 2.2: Full Load Efficiencies of Energy Efficient Motors - Closed Motors.

CHAPTER 3

EEM DESIGN AND CONSTRUCTION

As stated in Chapter 2, the direct way to improve motor efficiency is to reduce losses. This can be done through design improvements and the use of higher quality materials. The result is a rugged, long-lasting device with several energy saving features which include: improved steel properties, thinner laminations, increased volume copper conductors, modified slot design, improved rotor insulation, and more efficient fan design [Hirzel 1992]. Of course, these improvements increase the cost of the motor as most of them require an increased amount of active material and the use of lower loss magnetic steel [Andreas 1992, pg. 48]. However, using the above strategies has resulted in a general efficiency improvement trend such as the one shown for a 50-hp, 1800-rpm induction motor.

	1974	1975	1980	1985	1990	1995
Loss Reduction (Watts)	3950	3625	2625	2250	2050	1950
Efficiency (percent)	90.5	91.5	93.5	94	94.5	95

Table 3.1: Loss Reduction and Efficiency Improvement Trend for 50-hp, 1800 rpm Induction Motor [Andreas 1992, pg 51].

3.1. Design Parameters and Efficiency

The technical improvements to increase a motor's efficiency can be categorized into four areas: reducing I^2R losses, core losses, mechanical losses, and stray load losses. The first, I^2R losses, is created by current flowing through the rotor or stator. It is dependent not only on the current but also the winding resistance. The resistance can vary according to factors such as temperature and load. To compensate for these different variables, winding measurements are taken under a standard set of conditions. The DC resistance measurement is taken at the steady winding temperature attained where the motor is run at full load in a 25^{o} C ambient temperature. Resistance calculations are corrected to this standard and any error is assigned as a stray load loss [Mecker May 1994].

As the current is mainly a function of load, not much can be done to reduce its magnitude. The reactive current component can be improved with external capacitors. The best way to reduce losses to the motor itself is to improve the winding conductivity. For the stator this means increasing both the size and number of parallel conductors. Rotor losses are reduced by increasing the size of the conductor bars and using low-loss laminated steel. Larger motors use conductor bars instead of windings to reach maximum efficiency [Mecker May 1994]. Also, the reactive component of the total current demand can be reduced by decreasing the air gap between the stator and rotor. Consequently, a smaller magnetic field is needed to provide the flux for the same motor performance. The smaller magnetic field also requires less current.

Core loss is a result of hysteresis and eddy current. The core is a high-quality magnetic steel which the stator and rotor windings are formed on. The steel then focuses and directs the magnetic flux lines generated by the windings. Both the resulting magnetic

flux density (B - in tesla) and magnetic field intensity (H - in A/m) change with the fluctuating AC current and the plot of B vs. H is called a hysteresis loop. The area within the loop is proportional to the energy loss (as heat) in the core.

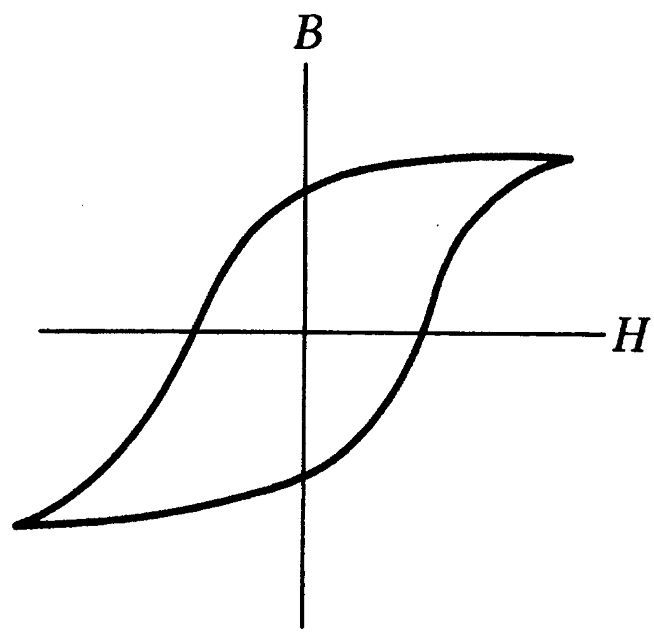

Figure 3.1: Hysteresis Curve [Serway 1986, p 690].

Using high-quality electrical steel in the core decreases the hysteresis loss and results in a narrower hysteresis loop. Typical carbon steel will have losses of 4.5 to 5 watt per pound (W/lb). Silicon steel, however, only has losses of 2.5 W/lb or less at the same flux density level. Unfortunately, silicon steel can cost twice as much as carbon steel [Mecker May 1994]. Silicon steel also doesn't perform well during the rewind process. If a motor should fail, the old windings are usually burnt off. This intense heat affects silicon steel

much more than carbon steel and so after a rewind the motor could have higher losses than before.

The second factor in core loss is eddy current. It is induced in the core by the varying magnetic fields and produces heat due to the I^2R losses in the core material. It provides no useful work, only generating heat. These losses are minimized by laminating the core from the sheets of steel that are insulated from each other [Mecker May 1994]. Also, using thin sheets of steel even further reduces the eddy currents.

Mechanical losses are the result of friction and windage within the motor. Windage is the loss from moving parts like the cooling fan - essentially another type of friction. Bearings are also another major source of friction. At motor start-up, the problem is even worse until the break-in period is over and the bearings function more closely together [Mecker May 1994].

Stray load losses are the catch-all, fudge factor, for motor design. They include items such as conductor skin effect, conductor geometry, and sloppy laminations. The most cost-efficient way to reduce stray load inefficiencies is to encourage a quality manufacturing process. A comprehensive summary of all these design considerations is outlined in Table 3.2. Specifically, it also shows adverse effects which can result from the design changes made to improve the motor efficiency. Engineers who design and specify motors have to take these factors into consideration in determining the trade-offs needed to achieve a certain efficiency. Part of this trade-off are improvements not inherent to the motor and less costly. Items such as power factor correction, loading, voltage, and system losses are considered in Chapter 7.

Losses	Possible Design Changes	Positive Effect on Losses	Adverse Effects
Stator Loss - W_s ($I_S{}^2R_S$)	1. Increase stator slot size & size of copper wire in slot.	1. Decrease stator resistance.	1. Increased cost & difficult to build.
	2. Decrease length of coil extensions.	2. Decrease stator resistance.	2. Possible increase of inrush current - difficult to build.
Core Loss - W_c (Hysteresis/Eddy Current)	1. Change to lamination steel of lower losses per unit wt.	1. Decrease hysteresis loss.	1. Increased cost & reduced availability of materials.
	2. Decrease lamination steel thickness.	2. Decrease eddy current loss.	2. Increased cost & reduced availability of materials.
	3. Improve coreplating/ annealing processes.	3. Decrease eddy current loss.	3. Increased cost & use of energy.
Rotor Loss - W_r ($I_r{}^2R_r$)	1. Increase flux density in air gap.	1. Decrease in slip and resulting I^2R_r.	1. Increase of inrush current.
	2. Increase rotor bar size.	2. Decrease rotor resistance.	2. Possible increase of inrush current & decrease of starting torque.
	3. Increase end ring size.	3. Decrease rotor resistance.	3. Possible increase of inrush current & decrease of starting torque.
	4. Increase rotor bar/ end ring conductivity.	4. Decrease rotor resistance.	4. Possible increase of inrush current & decrease of starting torque.

Table 3.2: Summary of the Actions That Can Be Taken to Improve Efficiency, continued on next page [Bonnett 1994b].

Losses	Possible Design Changes	Positive Effect on Losses	Adverse Effects
Windage & Friction Losses - W_{fw}	1. Optimize fan design to increase air flow.	1. Reduced operating temperatures.	1. Can cause increase in noise levels. May result in unidirectional fans.
	2. Optimize bearing selection.	2. Reduced friction loss.	2. May affect noise level or impose speed or bearing loading restriction.
Stray Load Loss - W_L	1. Insulate rotor bars.	1. Reduced bar to lamination currents.	1. Increased cost.
	2. Increase air gap.	2. Reduce high frequency surface losses.	2. Reduced power factor.
	3. Eliminate rotor skew.	3. Reduce W_r.	3. May increase noise levels & affect speed torque characteristics.
	4. Strand depth.	4. Reduced eddy currents.	4. Difficult to build, high cost.
	5. Transposed turns.	5. Reduced eddy currents.	5. Difficult to build, high cost.

Table 3.2: Summary of the Actions That Can Be Taken to Improve Efficiency, continued [Bonnett 1994b].

The ability to consider different combinations of improvement factors in motor design has greatly increased over the years with improvements in computing capability and software design. One routine [Chiricozzi et al 1997], optimizes the combination of different design variables to maximize the desired outcome -- efficiency, manufacturing and life-cycle cost, or both. It reduces the motor to an equivalent model whose simulation results prove quite close to actual motor testing.

The motor model is taken to its equivalent circuit parameters, namely resistances and inductances. The model considers the influence of saturation on rotor and stator reactances and the influence of skin effect on rotor parameters. A detailed thermal model also accounts for the effect of temperature on motor resistances.

The constraints placed on the design parameters by the motor's physical dimensions are what define the optimization function. These variables include: stator and rotor diameters, stator length, air gap size, stack length, stator slot depth, inner rotor tooth width, inner rotor slot opening width, inner slot opening depth, and outer rotor slot width. Each of these variables can then be varied between an upper and lower limit, in order to obtain a final optimized design whose dimensions are consistent with the frame of a standard motor with the same horsepower. The designer can leave some of the variables fixed in order to maximize the effectiveness of those which can be physically or affordably changed. It may not be possible for the designer to optimize all these parameters at the same time as well. In other situations, the motor variables conflict with each other and the designer must make compromises and prioritize which design parameters are the most important [Bonnett 1997].

The optimization function also considers performance characteristics such as starting torque, starting current, breakdown torque, rated power factor, stator winding temperature rise, rotor bar temperature rise, rated slip, and slot fullness. Once the performance and constraint equations are defined, the desired performance factors can be optimized through an iterative routine. This results in finding the best combination of material selection and motor design to optimize such characteristics as: rated efficiency; manufacturing

cost; starting torque; total cost (manufacturing and operating cost); and total cost with starting torque improvement.

The experimental motors built to the specifications outlined in the optimized simulation verified the routine's effectiveness. The motors constructed from the simulation parameters had results very close to those predicted by the routine. These tests were conducted for three-phase and single-phase induction motors under different optimization strategies. An added benefit was as the motor efficiency levels increased, the heat transfer capabilities of the mechanical parts also increased. A generalization of the differences between standard and energy-efficient motors is shown in the following table.

Part	Standard Motor	Energy Efficient Motor
Electrical Steel	2.5 - 3.0 Watts/lb	1.5 - 2.0 Watts/lb
Lamination Thickness Range	0.0185" - 0.035"	0.0185" - 0.025"
Slot Combination of Rotor and Stator	Same	Same
Stator Slot	Small	Large
Rotor Slot	Single or Double Cage	Single or Double Cage
Rotor Skew	Range from 0 to one slot	Range from 0 to one slot
Air Gap	Normal	Same or Slightly Larger
Rotor Construction	Die Cast	Die Cast
Winding	Machine or Hand Wound	Machine or Hand Wound

Table 3.3: Key Design Differences Between Standard and Energy Efficient Motors [Bonnett 1997].

It should be noted the information about air gaps contradicts what was mentioned previously in Section 3.1 from Mecker. There are different viewpoints about motor air gaps. Another author [Bonnet 1997] states that "Increase the air gap and harvest the resulting reduction in stray load loss until magnetic saturation occurs in the teeth or core of the lamination and the resulting increase in core loss is unacceptable." The air gap can't be increased too far before this occurs so usually there is no change in air gap distance.

3.2. Reliability, Quality, and Performance of EEM's

While these improvements are applied to increase motor efficiency, they are not meant to do so at the expense of overall motor performance and reliability. Some may feel the compromises made to achieve efficiency increases can reduce the motor lifespan or other performance characteristics. Generally, this is not the case. One indication is EEMs typically run cooler than standard efficiency motors, leading to longer insulation and bearing life [Brethauer et al 1994]. In addition, EEMs also tend to use heavier duty bearings which can prolong motor life even if proper lubrication practices are not followed [Nadel et al 1992, pg. 42]. This was demonstrated by some testing of energy efficient units [Bonnett 1997].

One factor having the largest impact on motor efficiency is winding temperature. Relations derived from IEEE Standards 117 and 101 demonstrate winding life is doubled for every 10^{o} C reduction in average operating temperatures. Testing by Bonnett [Bonnett 1997] showed a significant reduction in the average winding temperatures within the 3 - 50 hp range. Consequently, the motor's life could reasonably be expected to lengthen.

An examination of the EEM locked-rotor amps (as defined by NEMA) showed no significant difference with the standard efficiency motor. This was also true of the locked

kVA/hp or motor code letter. Therefore, none of the design changes made to EEMs would indicate a reduction in motor life based on locked rotor amps and locked kVA/hp. At the moment, however, there is no long-term motor life data to back this up.

Sampling of torque for energy efficient and standard motors show they do not vary significantly as well. For smaller energy efficient motors, testing demonstrated they had a lower slip. The lower slip levels result in a reduction in rotor losses and temperature, yielding a longer rotor and bearing life.

A comparison of the inductive reactance to resistance ratio found no significant difference between standard and energy efficient motors up to 100 hp. The assumption that the X/R ratio was increasing with efficiency has been used to explain why nuisance tripping of instantaneous breakers has increased. A more feasible explanation is related to the NEC limit of 7 to 13 times the full load current for the setting of instantaneous breakers while improvements in motors have led to more robust designs with increased starting torques and inrush currents, invalidating the current NEC practice. While the X/R ratio is affected by a reduction in winding resistance, it appears to not significantly change between standard and energy efficient motors. Chapter 4 goes into more detail on this subject and provides an understanding of nuisance tripping and its causes.

Additionally, EEMs have little effect on bearing life. The 10 - 15 rpm speed increase with EEMs has little impact. The main factor in bearing life is still lubrication and proper sealing.

The result of this testing works to disprove two myths about energy efficient motors [Bonnett 1997]:

1. "Energy efficient motors have shorter life because they have been designed with less margin."

2. "Due to the reduction in slip and the corresponding increase in revolutions per minute, energy efficient motors use more energy on variable torque applications such as pumps and fans that follow the affinity laws; i.e., required horsepower is proportional to the cube of the load."

The first statement is discounted by looking at the EEM design. In general, they have more active material, a higher quality electrical steel, run cooler, and therefore have a longer life.

The second statement is not necessarily true. For most applications using pumps and fans, the goal is to move a specific amount of fluid or air. The energy required to accomplish this task is the same whether a long or short time is used. Therefore, if the EEM, which will run slightly faster, can accomplish the job quicker, there should be no net increase in energy consumption. All of these tests show the transition to higher efficiency need not sacrifice motor performance and reliability. In fact, the use of higher quality materials can have the effect of decreasing operating temperature and improving life expectancy.

CHAPTER 4

INRUSH CURRENT AND NUISANCE TRIPPING

Over the past 30 years, there has been a gradual increase in the inrush current and starting torque of induction motors [Bonnett 1997]. This is a result of general improvement in motor design as well as the use of energy efficient motors. While Bonnett [Bonnett 1997] noted there was not a significant difference between the X/R ratios of standard and energy efficient motors, the ratio still plays a role in determining the inrush current of induction machines. The inrush current can greatly exceed the full load current, even the 7 to 13 ratio allowed by Article 430 in the National Electric Code. This disparity can cause frustration for motor users, especially those applying energy efficient machines which tend to have a higher relative starting current than standard motors [Nailen 1986] and may nuisance trip more often. One response is to increase the instantaneous trip ratio of starting current to full load current to 17. This accounts for the seven or more times increase of locked rotor current over full load current. The DC offset of the locked rotor current can be sqrt(3) times the rms current and the peak value being sqrt(2) times the rms current. The total product of these factors is 17.12 [Heath and Bradfield 1997]. However, this definitely violates the NEC. A clearer solution requires an understanding of the inrush current phenomena.

4.1. Coordination Problems

The ratio used to determine the setting of instantaneous protection devices in motor control is locked rotor or starting current divided by full load current. NEMA MG1-1.54-1993 defines locked rotor current as "the steady-state current taken from the line, with the rotor locked and with rated voltage (and rated frequency in the case of alternating current motors) applied to the motor." In the NEC, Article 430-52 and Table 430-152, locked rotor current is assumed to be less than eight times the full load current for a motor at the rated horsepower. The instantaneous trip device is then set at eight times full load current to allow for any variation in motor starting. In general, high efficiency motors have a larger ratio than standard motors [Heberlein 1989]. This energy efficient full load current at a given horsepower is less than for a standard efficiency motor, the stator and rotor impedances are less, and so the ratio to locked rotor current increases [Heath and Bradfield 1997]. This is one cause for nuisance tripping but is easily accounted for with a linear increase in the trip setting as the full load current decreases.

While locked rotor current usually doesn't present a problem, transient or inrush current can cause nuisance tripping. A large inrush current lasting a short period of time, up to a few cycles, can develop once the motor contactors are closed. This starting current begins as an asymmetrical locked rotor current which peaks during the first half-cycle and rapidly decays to a steady-state value. While most motors do not have a locked rotor current which exceeds 10 to 13 times the full load current, high efficiency motors can exceed this value. Their inrush current can reach 1.8 to 2 times the locked rotor current [Heberlein 1989]. This peak is what the instantaneous time circuit breaker reacts to in nuisance tripping and is shown in Figure 4.1.

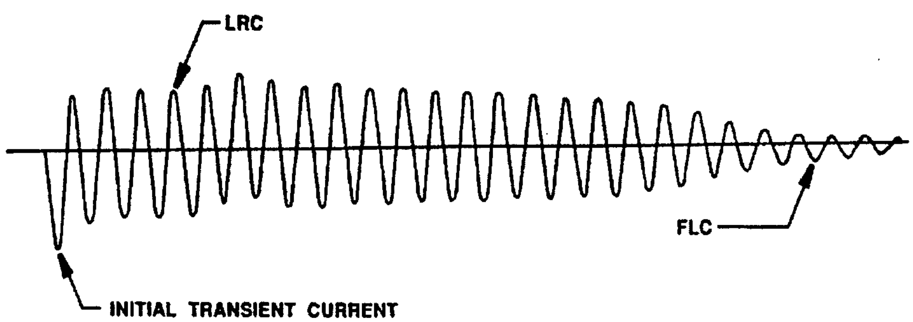

Fig 4.1. One Phase Trace of Motor Starting Current [Heberlein 1989]

The cause of the higher inrush current in energy efficient motors is related to the asymmetrical starting current and the X/R ratio. The current is described by summing the voltages around the circuit of Fig. 4.2 and then solving the nonhomogeneous first order differential equation which gives [Hartman 1985] the sum of the decaying dc and ac current components:

$$I = I_o\{\sin[\tan^{-1}(X/R) - \theta] * \exp[-2\pi ft/(X/R)] + \sin[2\pi ft + \theta - \tan^{-1}(X/R)]\} \qquad (4.1)$$

where: I_o = peak symmetrical current, amps; t = time, seconds

X = reactance value per phase, ohms; R= resistance value per phase, ohms

θ = voltage phase angle when motor started, radians

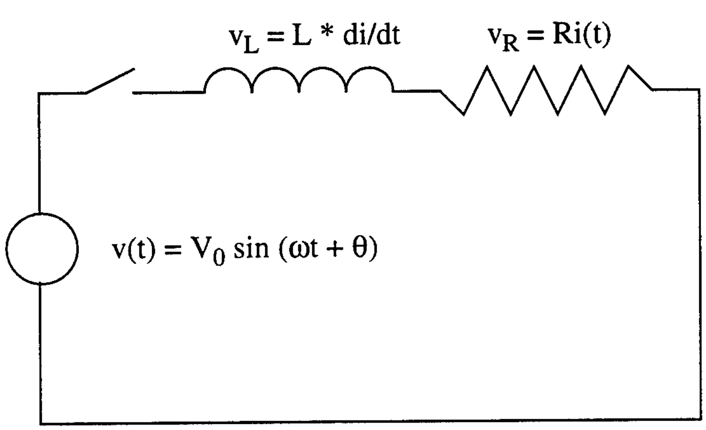

Fig. 4.2. Asymmetrical Circuit Model.

When the motor contactors close with a voltage angle of zero, maximum peak current results for a given X/R ratio. Since the equivalent motor model is an inductive circuit (Fig. 4.2), the voltage and current will be close to 90 degrees out of phase, depending on the ratio of X to R. The angle of displacement is equal to $\tan^{-1}(X/R)$. When the circuit is purely inductive the current wave will lag the voltage wave by 90 degrees. As resistance is increased the current will go from 90 degrees lagging to 0 degrees lagging (in phase) for a purely resistive circuit [Hartman 1985].

Then, if the motor contacts close when the voltage source magnitude is zero ($\theta = 0$ degrees), the inductive current will reach its peak value (see Fig. 4.3). This is because the rate of change of the current is proportional to the voltage across the inductive elements. As the voltage increases, the rate of change of the slope increases proportionally. The slope continues to increase until the voltage reaches its peak at 0.25 cycle. As the voltage decreases the current stays positive but its slope decreases. At 0.5 cycle the voltage turns negative and so does the current slope. The current continues decreasing until the voltage becomes positive again and the current slope turns positive also. The current experiences a complete voltage cycle and so it reaches the maximum asymmetrical current value. This occurs at time corresponding to about 0.5 cycle, i.e., at about 8.3 ms when the voltage waveform starts with zero magnitude ($\theta = 0$ degrees) at time zero.

However, if the contacts close when the voltage is at a maximum ($\theta = 90$ degrees), the current does not experience the full voltage cycle and it does not reach its maximum peak [Hartman 1985]. The current is symmetrical about the zero current axis (Fig. 4.3).

This is a result of the same voltage and slope comparison used to determine the asymmetrical current waveform.

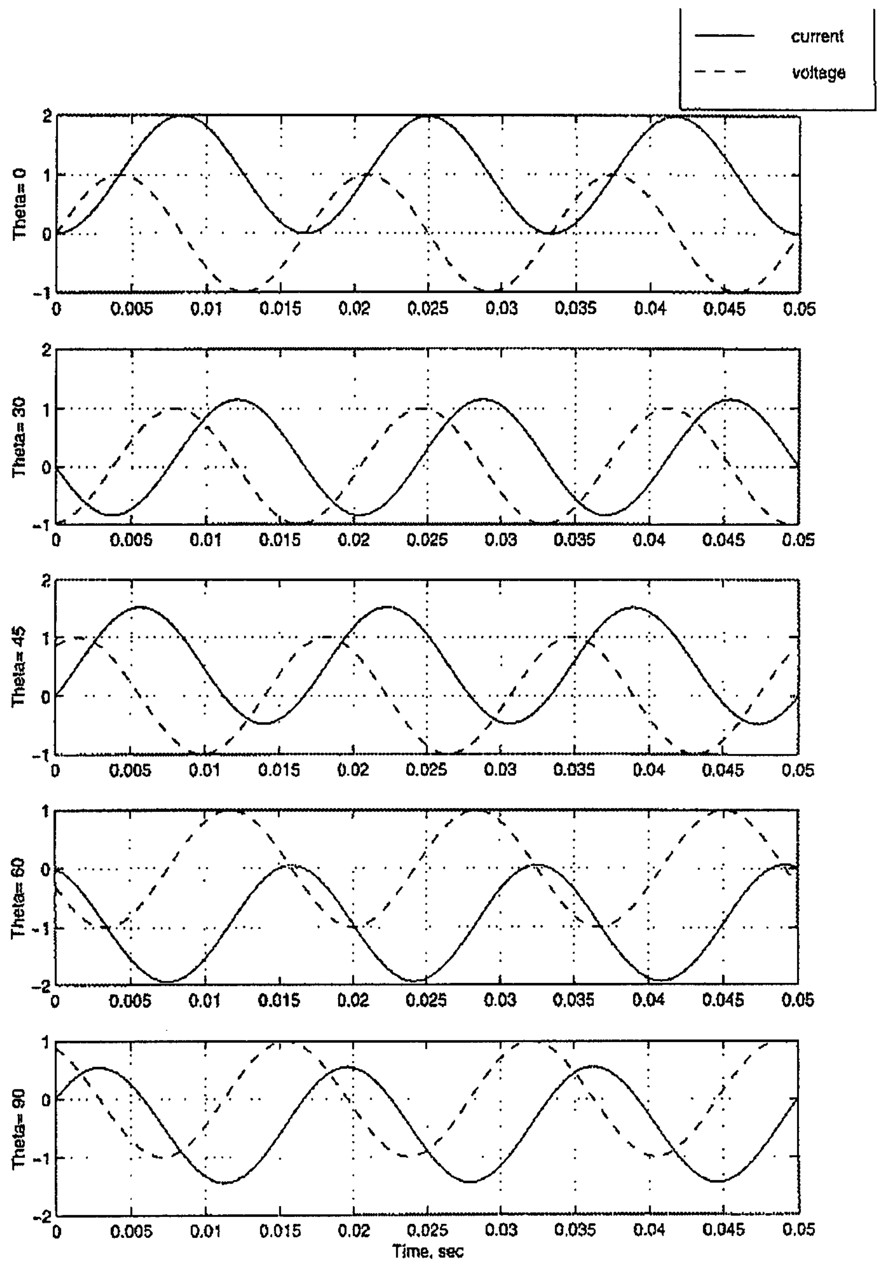

Fig. 4.3: Current and Voltage Curves for Various Closing Angles (X/R=1000).

The closing angle can happen at any time though and so nuisance tripping may or may not occur depending on the current voltage angle value. Fig 4.3 shows plots for various closing angles and an X/R ratio of 1000 (mostly inductive circuit).

The magnitude of the inductive current defines the first factor affecting inrush current, the second component is the amount of asymmetry or dc current component. This is where the X/R ratio has an impact. Using (4.1), the maximum dc offset occurs at:

$$\theta = \tan^{-1}(X/R) - \pi/2.$$

Also, Figure 4.3 shows that if the voltage waveform starts at time zero then the inductive current reaches its peak value at a time corresponding to about 0.5 cycle.

Substituting these assumptions for time and θ into (4.1) gives:

$$\begin{aligned} I &= I_o\,\{\sin[\tan^{-1}(X/R) - \tan^{-1}(X/R) + \pi/2] * \exp[-2\pi * (1/2)/(X/R)] \\ &\quad + \sin[2\pi * (1/2) + (\tan^{-1}(X/R) - \pi/2) - \tan^{-1}(X/R)]\} \\ &= I_o\,\{\sin[\pi/2] * \exp[-\pi/(X/R)] + \sin[\pi - \pi/2]\} \\ &= I_o\,\{1 * \exp[-\pi/(X/R)] + \sin[\pi/2]\} \\ &= I_o\,\{\exp[-\pi/(X/R)] + 1\}. \end{aligned} \tag{4.2}$$

With (4.2) there is a direct relation between the peak inrush current and the X/R ratio, assuming worst-case conditions for all other factors. Table 4.1 shows the peak asymmetrical current for increasing values of X/R. As X/R becomes infinitely large the

X/R	I_{peak} maximum asymmetry	X/R	I_{peak} maximum asymmetry
0.1	1.000	5	1.533
0.2	1.000	10	1.730
0.3	1.000	15	1.811
0.4	1.000	20	1.855
0.5	1.002	25	1.882
0.6	1.005	30	1.901
0.7	1.011	35	1.914
0.8	1.020	40	1.924
0.9	1.030	45	1.933
1	1.043	50	1.939
2	1.208	100	1.969
3	1.351	1000	1.997
4	1.456	inf	2.000

Table 4.1: Maximum Fault Current.

current approaches the theoretical limit of twice the peak symmetrical current. What is in dispute is whether energy efficient motors increase this ratio. At face value, the EEM uses larger conductors so the stator and rotor winding resistance is lower and, so, the X/R ratio should be larger than a standard motor's. Some testing [Bonnett 1997] has shown this is not the case, however, and standard and efficient motors have very similar X/R values up to very large rated horsepowers. While X/R does play a role in peak current, as shown by (4.2), the increased robustness of new motor designs must also be considered. Perhaps,

what testing has proven is modern motors are becoming more and more efficient and the gap between standard and efficient machines is shrinking.

Also, the X/R ratio may not be directly available either. This is especially true in fault calculations which must consider many more things than one specific motor. Additional items which affect the equivalent circuit impedance include other motors, cable impedances, and transformers. These would all need to be included in an X/R used in calculating currents under a fault condition.

Over the past decades, the inrush current has been increasing and motor controls are also becoming more stringent. The following four factors [Scheda 1986] have played a role in this trend:

1. New electronic monitoring devices which control motors by responding to instantaneous values are beginning to dominate the industry.

2. NEMA and NEC standards governing the design and application of induction motors regulate steady-state performance only.

3. High-efficiency motors that have the same steady-state inrush (locked rotor current) as a standard motor will have higher peak transients. This peak is what the instantaneous time circuit breaker reacts to in nuisance tripping.

4. Large motors have a higher relative transient inrush than smaller machines even though they meet NEMA maximum steady-state requirements.

Based upon the preceding factors, the two most commonly encountered problems are [Scheda 1986]:

1. A standard motor is replaced by a high efficiency unit and the electronic control begins to nuisance trip (the trip setting must be higher).

2. On larger machines, thermal type current sensors (inverse time breakers) must be used since higher settings for the electronic control would violate the NEC.

The understanding of nuisance tripping and its causes can now help in developing a practical solution to these situations. The ideal answer should let the motor start without trouble and still protect against mid-range faults. Additionally, a solution must fall within the boundaries set by the NEC.

4.2. Solutions

Considering improved design and the possibly larger X/R ratios, inrush currents are exceeding the locked rotor to full load current ratio of 13 established in the NEC. This is due in part to full load currents decreasing compared to those of thirty years ago when the full load motor currents in Article 430 (NEC) were first established. As noted [Scheda 1986], the prevalence of instantaneous trip electronic circuit breakers has made this larger inrush current a problem. Sometimes it exceeds the ratio of 13 and nuisance tripping results. There is little room in the motor protection coordination system to let these short lasting, large currents through. Generally, this did not occur with inverse time circuit breakers which preceded the advent of instantaneous trip breakers. However, they did not provide tight coordination with the motor's thermal element which protected the motor in the event of an overload. A damaging fault current could then flow until detected by the thermal element. This could take several seconds or more, resulting in severe damage to the motor windings.

As a consequence of nuisance tripping, motor applications may require one of the following [Heath and Bradfield 1997]:

1. Setting the instantaneous breaker higher than 13 times the full load amps in violation of the NEC.

2. Using an inverse time circuit breaker for which the NEC does not specify any limit for instantaneous operation and which may not provide adequate short circuit protection for low level faults.

3. Using an instantaneous trip breaker with damping means (not commonly available).

Inverse time breakers do protect against large fault currents and allow the locked rotor inrush current to flow when it exceeds 13 times the full load current. However, the instantaneous setting may be too high to provide adequate protection. Bradfield and Heath provide a good example of this [p 42]:

> "Consider a 460 Vac, 40 horsepower energy efficient motor which the NEC Table 430-150 claims 52 full load amps. A thermal magnetic breaker sized to 250 percent full load amps is selected. Since a 130 amp (2.5 * 52 = 130 amps) rating is not a standard ampere rating, a 150 amp fixed instantaneous breaker is selected. The actual instantaneous pickup is 2,250 symmetrical rms amperes or 15 times the breaker ampere rating. This breaker will not respond instantaneously until a current of 2,250 symmetrical rms amperes or 3,181 peak amperes flows. The 40 horsepower motor's first half-cycle inrush is found from the manufacturer to be 629 peak amperes (12.1 times full load amps).
>
> There will be no problem starting the motor, but a short circuit current of, for example, 1,900 amperes will not be cleared until the thermal portion of the trip unit responds in, typically, several seconds. (While not acceptable by the NEC, an instantaneous trip breaker set at, for example, 16 times full load amps will provide tighter short-circuit protection than an inverse time breaker whose fixed instantaneous will not operate until a fault escalates to 30 or 40 times full load amps)."

One proposed solution [Heath and Bradfield 1997] combines the concept of instantaneous and inverse time breakers. There is a large gap between the starting inrush current and the current magnitude which would instantaneously trip the breaker as shown in the previous example. An inverse trip breaker with an adjustable instantaneous setting can correct the situation. An instantaneous breaker may interfere with a motor's starting current unless set beyond the NEC 13X full load ampere threshold. However, as seen above, an inverse time breaker won't be set at that current level. Also, the instantaneous adjust-

ment can be set just beyond the motor's peak starting current. This does not violate the NEC and still avoids nuisance tripping. The motor can then start without interference and still be protected against intermediate range faults. This is shown in Figures 4.4 and 4.5.

For this motor, the peak inrush current is 791 amps rms and is at the 0.01 second horizontal axis in Fig. 4.4. Fig. 4.5 shows an enlarged view of this area. Fig. 4.4 also shows the full load amperes of 65.3 amps rms and locked rotor amps of 457 amps rms. The instantaneous breaker "interferes" with the peak inrush current but the inverse the breaker instantaneous pickup, set at 1000 amps rms, does not. This is seen by the gap between the two curves in Fig 4.5.

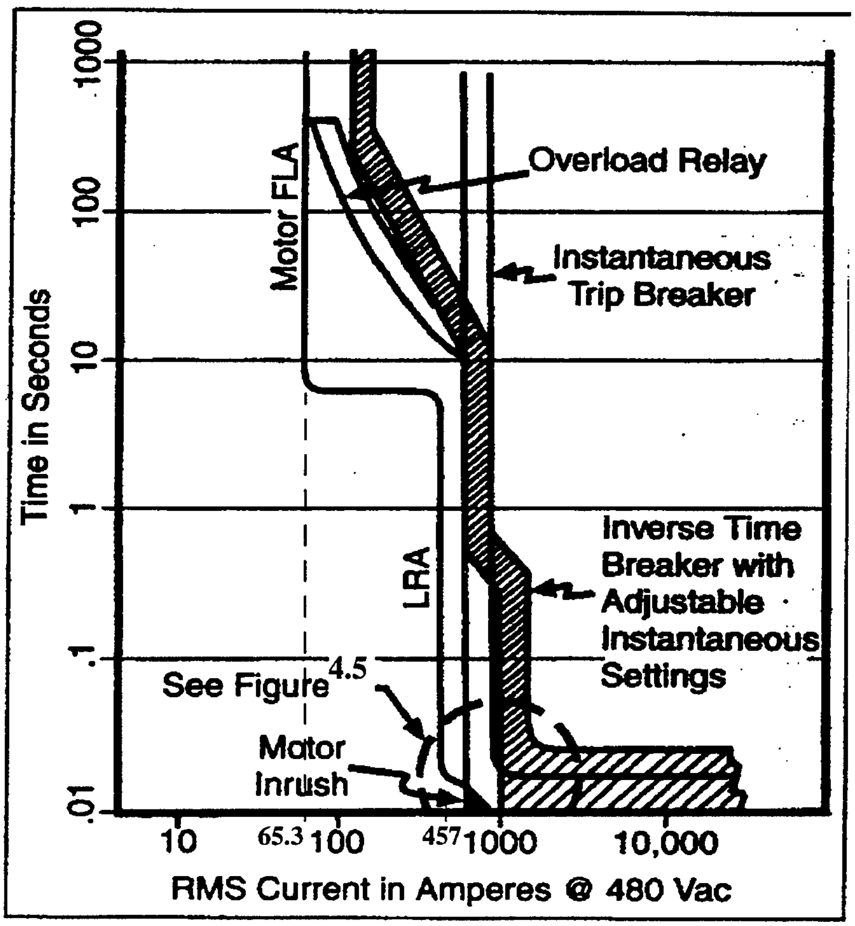

Fig. 4.4: Time-Current Coordination Plot [Heath and Bradfield p 43].

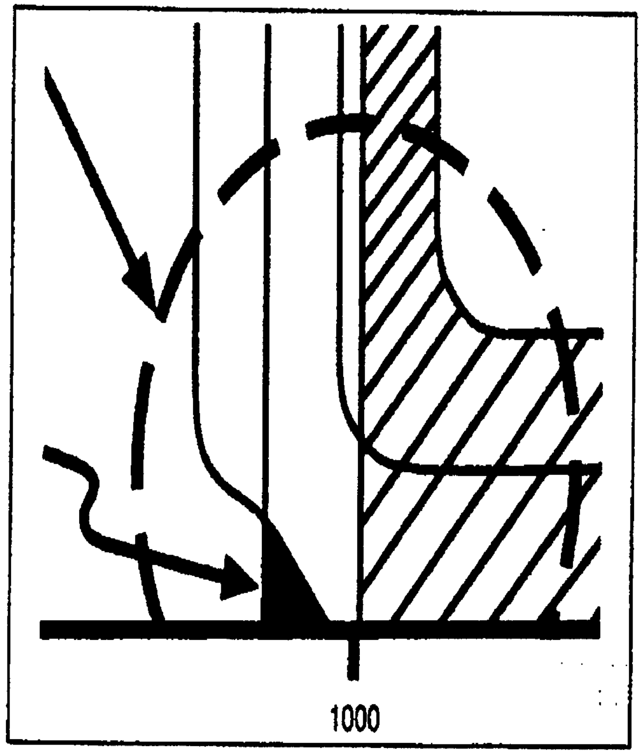

Fig. 4.5: Enlarged View of Motor Inrush [Heath and Bradfield p 43].

While a good solution, adjustable inverse time breakers don't need to be used in all cases. An inverse time breaker without an adjustable instantaneous trip can work well and still protect the motor. Conversely, an instantaneous breaker is suitable if it can avoid nuisance trips without being set beyond 13X the full load current.

The first step is to obtain an accurate value of the inrush current prior to acquiring the device for short circuit and ground fault protection. Afterwards, the appropriate decision can be made about the protection device as it relates to starting, cost, and feasibility.

CHAPTER 5

REWINDING

While electric motors are one of the most efficient and reliable energy conversion devices around, eventually they can and do fail. This failure brings several choices to the attention of the owner or user. First, of course, is the cost. Then, to decide whether it is less expensive to repair or replace the damaged unit. The cost basis must include any change in efficiency might have on the life-cycle operating costs. This is explored more fully in Chapter 6. Also of importance is how long it will take to get the driven equipment running again.

In most cases, the motor's bearings or windings fail and so only the damaged components need replacing after which the motor is reassembled. The rebuilt motor can use the same rotor and stator iron and case, leading to considerable savings in raw materials. The process of stripping out old windings and replacing them with new wire is called rewinding [Nadel et al 1992, p. 43].

If the decision maker takes a little more time or considers the alternatives before a quick decision becomes necessary, then the importance of motor efficiency becomes apparent. The correct choice can save the operator many times their initial investment in an energy efficient motor or rewind. Likewise, the incorrect choice can have an equally

deleterious impact on energy costs. A poor rewind or less efficient motor will negate any short-term gains in low initial cost. Of course each replacement scenario may have certain conditions which do not justify increased motor efficiency, for instance low operating hours. However, in any case the owner should consider long-term operating costs, not just initial cost or rewind speed, in making the repair decision.

5.1. Causes of Insulation Failure

Motor windings fail when their insulation degrades, usually due to some combination of overheating, aging, and overvoltage transients. Minor insulation failure can lead to poor motor performance, shock, and fire hazard. Major insulation failure will result in a fault and trip the overcurrent protection devices [Nadel et al 1992, p. 43]. Aging magnifies the effects of dust and other solid contaminants, chemicals, moisture, and vibration. Overheating results from overloading and also from the ambient operating temperature while undervoltage, overvoltage, voltage unbalance, and voltage surges also contribute to winding failure [Strugar and Weiss 1994].

Aging begins as dust and other solids make their way inside the motor casing. Therefore, it is important to keep the motor as clean as possible. Sand, glass, stone, slag, metal shavings, and other forms of grit abrade winding insulation and attack motor shaft bearings. Adhering to the motor manufacturer's recommended lubrication schedule alleviates the effects of abrasive dusts in bearing grease. Conductive dust found in tire manufacturing plants, some metal working facilities, and coal-handling applications present special problems. As these particles settle into the winding loops, they can become embedded in the insulation by the operating motor's natural vibration. This severely

weakens the insulation by providing greater opportunities for short-circuits and greatly contributes to insulation failure.

Chemical fumes and moisture are another source of insulation degradation. Corrosive chemicals attack not only the winding insulation but also the physical housing, rotor shaft, and bearings. This corrosion to nonelectrical components can be prevented with an epoxy coating. The operating environment doesn't necessarily need to be corrosive to damage windings. Their are many liquids and fumes which attack motor insulation systems and some solvents degrade the insulation varnish as well. However, the user can specify certain varnishes which are impervious to various types of chemicals.

Sustained water moisture, while it contains no corrosive chemicals, can also penetrate motor windings and result in the failure of conventional insulation varnishes. Specially formulated, water-resistant varnishes exist which can be used in machines operated in an especially moist or humid environment. In cases where the motor is operated fairly regularly, the heat generated from the machine is usually enough to evaporate moisture and prevent condensation on the windings. For motors in a standby mode or infrequently operated, heat lamps or space heaters may be needed in the motor housing to keep away moisture.

The last age related problem is vibration. Vibration damages motor bearings and can crack winding insulation which leads to winding failure. The cause of the disturbance can be within the motor itself or the driven load. Some sources include [Strugar and Weiss 1994]:

1. Misalignment of motor and load.
2. Motor or load shaft bent.
3. Motor or load mounting loose.

4. Eccentricity of motor or load rotating elements.
5. Accumulation of foreign materials on rotating elements.
6. Worn bearings.
7. Imperfect castings in motor rotor.
8. Motor rotating element resonance.
9. Structural or torsional resonance.

These, or any, causes should be eliminated as quickly as possible and an ongoing detection program put in place to discover new sources of vibration.

Motor overheating is the most prevalent source of winding failure. It is caused by either overloading the motor or operating the device in an ambient temperature beyond the insulation rating. In either case this severely degrades the winding insulation. A commonly accepted rule of thumb states that for every ten degrees celsius that a motor winding operates above the design temperature - even for brief periods - winding insulation life is halved [Strugar and Weiss 1994]. A motor can become overloaded either because it was undersized in the first place or the load has increased over time. The situation should be assessed and a proper motor size applied so it does not draw more than its nameplate current rating and overheat.

A high ambient operating temperature is also cause for concern and should initiate a check of motor cooling systems. The motor housing and fan passages must be kept clean to optimize heat transfer. They should also be shielded from external heat sources or else supplied with cooling air. A good way to ensure the correct operating environment is to check the motor nameplate temperature rating and see it is not exceeded.

Voltage aberrations compose the last segment of possibilities which can potentially damage motor windings. Undervoltage and overvoltage reduce insulation life for the same reason overloading does. For undervoltage the resultant load on the motor increases

(if the connected load is constant) and the winding current increases. Overvoltage directly causes the current in the windings to increase. In either case the motor temperature rises and winding life decreases. Voltage unbalance causes this problem on an even greater scale. A slight unbalance results in significant current increase in two phases, and the associated overheating. This is a very detrimental problem and should be corrected quickly. Voltage surges can also cause winding failure. A sharp increase in current, caused by a voltage spike, can expose any weak spots in the winding insulation and lead to its breakdown [Strugar and Weiss 1994].

All of these environmental stresses can lead to the degradation of winding insulation and motor failure. The machine can usually be repaired but the owner must assess the impact rewinding will have and what the long-term cost will be.

5.2. Impact on Efficiency

A general consensus covering rewind effects on motor efficiency can be summed up as follows: "The general conclusion is that the depreciation in efficiency is not significant when recommended rewind practices are followed ... " [Bonnett 1995]. The practice which has the largest impact on efficiency is stripping the failed windings. The faulty winding insulation is often broken down by heating at a very high temperature in an oven. However, excessive temperature can destroy the laminations in the rotor core [Nailen 1992]. Motor cores are insulated between the laminations to minimize eddy currents, but improper stripping can destroy this insulation. Therefore, when stripping a motor for rewind, insulation burnout must be done at carefully controlled temperatures so as to not affect the core laminations. Otherwise, it is too easy to overheat the laminations, breaking down the insulation in the core and actually increasing the core loss [Hirzel 1994].

Motor repair shops are well aware of this problem and have taken steps to prevent core lamination degradation. Oven temperature control can be used to ensure critical levels are not exceeded. There is no safe burn-out temperature for all motor cores and so it is important to know what type of insulation is used. Organic lamination insulation will begin to deteriorate around 500^{0} Fahrenheit. Organic insulation can be damaged in any oven hot enough to burn out the winding insulation. Inorganic insulation can withstand temperatures up to 700^{0} Fahrenheit which allows the winding insulation to burn off. In all cases, damage can occur at a lower temperature when several cores are stacked in the oven and fire from the burning organic materials results in increased temperature beyond the oven setting [Hirzel 1994].

Alternatives to winding burn-out are also being explored to reduce the potential increase in core losses. These non-thermal methods include: mechanical stripping, chemical stripping, and high-pressure water jets [Hirzel 1994]. In general, motor rewinds do not greatly affect the machine's efficiency. Repeated rewinds of a ten horsepower motor show little change:

Rewind	Original	1	2	3	4	5
Percent Efficiency, at Full Load	89.2	89.2	89.2	89.6	89.6	89.6
Percent Efficiency, at 3/4 Load	90.1	90.1	90.1	90.1	90.1	90.1

Table 5.1: Percent Efficiency of a 10-hp Motor at 3/4 Load and Full Load for Repeated Rewind Operations [Nailen 1992].

Rewinding is an economical alternative when it is done correctly. Realizing the motor is an energy investment, the owner needs to make a decision which will stand for the long-term. If a rewind ends up being the best choice then the user should evaluate the stripping methods of prospective repair shops to ensure they follow recommended practices. It is especially a good idea to test the motor and make sure there was no increase in losses.

CHAPTER 6

COST SAVINGS

Electric motors are good candidates for energy savings. Continuous duty motors comprise only a fraction of those used in North America's industrial plants. However, these relatively few motors account for about 75 percent of all industrial electrical use [Hirzel 1992]. This is a great opportunity for energy and cost savings, however discretion must be applied when exploring possibilities. A proper analysis of each replacement situation should be made before deciding to replace a standard with an energy efficient motor. This is where a thorough grounding in cost analysis can be used to make the best choice.

The first issue is the time value of money and how inflationary pressures or utility rate increases can affect the long-term outcome of an investment. A simple method to calculate energy savings between two motors of different efficiencies is [Bonnett 1993]:

$$S = 0.746 * hp * C * N * (100/E_b - 100/E_a)$$

where

- S: savings in dollars per year
- hp: horsepower rating of the specified load
- C: energy cost in dollars per kilowatt hour
- N: running time in hours per year
- E_a: efficiency (in percent) of motor "A" at the specified load
- E_b: efficiency (in percent) of motor "B" at the specified load

The equation applies to motors operating at a specified load and provides an annual snap-shot of energy savings. What it doesn't offer is the long-term effect interest rates can have on cash flow.

Next, this analysis can be used to compare the different advantages of repairing a motor, replacing it (even if the original unit is not damaged), and using utility rebates (demand side management) to offset the initial cost outlay when a motor is replaced. Once all of these possibilities are considered, along with an accurate cost assessment, it is then much easier to make an informed decision.

6.1. Time Value of Money

The simplest way to evaluate an annual investment option is to calculate the net present value of the annual cash flows. A typical annual motor cash flow can consist of the following elements for any given year [Brethauer, Doughty, Puckett 1994]:

+	Savings from use of higher efficiency motor
-	Cash expenses (installation and maintenance)
-	Motor depreciation for incremental investment
=	Taxable income (Total)
-	Taxes at 37% (Federal and state)
=	After-tax income (Total)
+	Motor depreciation for incremental investment
-	Incremental investment for higher efficiency motor
=	Cash flow (Total)

The depreciation on the incremental investment is first subtracted from the savings to allow calculation of the taxable income, and then is added back to calculate the cash flow. This sequence of annual cash flows is then converted to a net present value for comparison with other cash flow series.

The key to comparing the present value of varying cash flow streams begins by examining the process of compound interest [White, Agee, Case 1989]. The interest rate

in compound interest is defined as "the rate of change in the accumulated value of money." By contrast, the annual interest rate in simple interest is the change in the value of one dollar over a one year period - it does not include the interest accumulation over previous years. Mathematically, simple interest accumulates by a value of P*i each year where P is the principal and i is the annual interest rate. The final accumulation after n periods is the interest earned plus the principal, or:

$$F = P + P*i*n = P*(1 + i*n) \tag{6.1}$$

Using compound interest to determine the future value requires converting the accrued interest for each period into principal for the purpose of calculating interest over the next period. For n periods, compound interest accumulates as follows:

$$F_n = P*(1 + i)^n \tag{6.2}$$

which quite readily demonstrates the time value, or opportunity cost, of money. For instance, if a guaranteed interest rate of 5 percent per compounding period is available the future value of $1,000 after five compounding periods is:

$$\$1{,}000*(1 + 0.05)^5 = \$1{,}276.28.$$

If, for some reason, the $1,000 was not available until after two compounding periods then the future value is:

$$\$1{,}000*(1 + 0.05)^3 = \$1{,}157.63.$$

The potential earnings lost is:

$$\$1{,}276.68 - \$1{,}157.63 = \$118.65.$$

Therefore, for those two compounding periods, the $1,000 must make at least $118.65 in some other investment or else it is better off earning the guaranteed five percent.

The converse of (6.2),

$$P = F^*(1 + i)^{-n} \tag{6.3}$$

can be used to convert a stream of payments to their present value. For instance, if the resultant cash flow total for an EEM installation is a positive $1,000 per compounding period (typically one year) then the net present value can be calculated as shown below (Table 6.1) for six years and a 12 percent discount rate [Brethauer, Doughty, Puckett 1994]. The discount factor is $(1 + i)^{-n}$ and so the present value is the principal times the discount factor.

Year End	Cash Flow ($)	Discount Factor	Present Value ($)
1	+1,000	0.893	893
2	+1,000	0.797	797
3	+1,000	0.712	712
4	+1,000	0.636	636
5	+1,000	0.567	567
6	+1,000	0.507	507
		Net Present Value	4,112

Table 6.1: Net Present Value of Six Year Cash Flow [Breuthauer, Doughty, Puckett 1994].

When comparing two cash flow options, say repairing a damaged motor instead of replacing it, the annual cash flow of each choice should be converted to a present value. The choice with the higher present value of savings is the most cost effective. This process takes the energy savings in future years and compares it with the initial savings of buying a less costly motor. The best value is the choice which provides the larger savings.

Using the time value of money is essential to accurately evaluate different energy options. It can bring to light different possibilities which may not be advantageous for the short-term but saves money for the operation over a longer operating period. There are different ways to use these methods in evaluating options. The simplest and most straightforward is net present value. However, if the number of expected useful years is fixed and the initial cost and the annual energy savings differential is known, an iterative process can find the interest rate which results in a payback of the initial cost over the predetermined time frame. This is the internal rate of return of the investment and should exceed the operations own cost of doing business. Other valuation possibilities are available but the most important thing to include is some adjustment for the opportunity cost.

6.2. New Installation

The chance to use energy efficient devices in the initial implementation of a process is usually a great opportunity. With increasing power costs, most process owners are forced to look at the total cost of owning a motor, not just the initial expenditure. For example [Hirzel 1994]: a 50 horsepower, 1800 rpm, totally enclosed, fan cooled motor sells for approximately $1,200. Its efficiency is 91.5 percent (standard efficiency) and operates continuously on electrical power that costs $0.07 per kilowatt-hour. In just the first year energy costs will be $24,997 or 20.8 times the first cost. The energy cost will equal the first cost in 18 days. If the motor is used for two shifts (4,160 hours per year), this will occur after 27 days; and if used for one shift it will take just 53 days. This is just a simple payback and does not even include the added impact of the time value of money.

In most cases installing an energy efficient machine over a standard efficiency is preferred. The main reason for this is the installation costs for either possibility are the

same and so can be ignored. Since all other factors for consideration are the same (i.e. energy cost, interest rate, inflation) the EEM usually will quickly recover its initial extra expense.

6.3. Repair Versus Replace

The decision to repair or replace a damaged motor can be a little more involved. Again, the installation charges can be neglected because they will be needed for either option. Table 6.2 shows the calculations justifying an additional expense of $3,487 with a six year payback. Depreciation is not included because the repair option would not have any depreciable costs. The energy efficient motor premium is justified as long as a six year payback period and a rate of return of 25 percent are acceptable. The variables are:

Motor Horsepower	500
Motor Load Factor	75%
New Motor Cost - Rewind Cost	$3,487
Rewound Motor Efficiency	94.4%
New Motor Efficiency	95.7%
Annual Operating Hours	8,000
Energy Savings	32,204.7 kWhr/yr
Cost of Energy	$0.035 $/kWhr
Energy Inflation	2.5 %/yr
Discount Rate	25%/yr

Year	0	1	2	3	4	5	6
Cost of Energy ($/kWhr)		$0.03500	$0.03588	$0.03677	$0.03769	$0.03863	$0.03960
Savings		$1,127.17	$1,155.34	$1,184.23	$1,213.83	$1,244.18	$1,275.28
Motor Cost Difference	($3,486.66)						
Less Deprecia-tion		0	0	0	0	0	0
Before Tax Income	($3,486.66)	$1,127.17	$1,155.34	$1,184.23	$1,213.83	$1,244.18	$1,275.28
Less Taxes (37%)	$1,290.06	($417.05)	($427.48)	($438.16)	($449.12)	($460.35)	($471.86)
After Tax Income	($2,196.59)	$710.11	$727.87	$746.06	$764.72	$783.83	$803.43
Deprecia-tion		0	0	0	0	0	0
Total Cash Inflow	($2,196.59)	$710.11	$727.87	$746.06	$764.72	$783.83	$803.43
Discount Factor	1.0000	0.8000	0.6400	0.5120	0.4096	0.3277	0.2621
Dis-counted Cash Inflow	($2,196.59)	$568.09	$465.83	$381.98	$313.23	$256.85	$210.61
Cumula-tive Dis-counted Cash Flow	($2,196.59)	($1,628.50)	($1,162.67)	($780.68)	($467.46)	($210.61)	$0.00

Table 6.2: Incremental Cost Dollars Justified to Purchase a Premium Efficiency Replacement Motor Versus Rewinding the Existing Motor [Brethauer, Doughty, Puckett 1994].

In this example the capital motor costs are represented as an expense. The difference between a new motor and a rewind is $3,486.66 and so it is entered as a cost. This cost is

then offset by savings from the energy efficient motor over six years. At the end of six years the extra investment is paid off at a discount rate of 25 percent.

In general, the economics will usually favor replacing a damaged machine with an EEM - mostly due to the energy savings from improved efficiency alone. This does not include other considerations such as the 0.2 to 0.6 percent efficiency decrease every time a motor is rewound [Campbell 1997]. The small decrease results from poorly controlled burnout temperatures and subsequent damage to the stator core. If the failed motor is older and has been rewound before then chances are the actual efficiency is less than the nameplate and another rewind could worsen the situation.

Other influencing factors include the motor's application [Campbell 1997]. If the motor is in an intermittent duty application and sees only limited usage then energy costs are not significant and it is probably less expensive in the long run to just repair the unit. Likewise, special duty motors and those built for specific applications may not have a suitable substitute available on the market. The only timely choice in these situations may be to just repair the damaged motor. This is a situation which should be corrected. If at all possible, the machines in a plant should be standardized making them easier to replace. This enables the user to take advantage of available energy efficient units and reduces repair and replacement costs as off the shelf parts and motors are easily obtained.

Process down-time is another consideration a user may face in the repair/replace decision. If it is important to have a motor constantly running then replacement is the only option. Here, the user could purchase an energy efficient or standard motor depending on the duty application and costs involved.

A last consideration in the repair/replace balance is the technology improvements available in newer motors. New advancements in today's severe-duty, off the shelf units were likely not available in older, failed motors [Campbell 1997]. The items listed below are some of these available features.

1. The class F insulation system is now a standard feature with most manufacturers. This means today's motor insulation life is much longer than previous designs because the temperature rise standards have not changed. Thus, modern motors must still withstand the same temperature rise as earlier motors but their winding insulation has a much greater thermal resistivity.

2. Larger bearings are now standard and so the bearing life is longer.

3. Improved balance levels are now used in standard motor designs so the vibrations are much lower and the bearing life is also improved.

4. Inner bearing caps provide protection against overgreasing. This keeps excess grease from getting on the stator.

5. External bearing isolators provide a labyrinthine seal to protect the motor from moisture or contaminants entering along the shaft.

It is hard to quantify all of these improvements in the traditional first cost and long-term energy savings quantization. However, they do provide a definite advantage to the replace option and should be considered as important elements of the total life cycle cost evaluation.

There is one important factor remaining which can have a dramatic affect on the most economical choice in the new application, repair vs. replace, or retrofit scenarios - utility rebates. It may be in the utility's best interest to reduce or stabilize the existing consumer load and thus postpone the construction of new generation capability. This strategy is also known as demand side management.

6.4. Demand Side Management

In the late 1980's and early 1990's, electric utilities began seeking alternative ways to reduce their rising costs. Electricity, the easiest form of energy to distribute and convert, sees few losses in the distribution and initial conversion process, but the potential for improvement still exists. The activities electric utilities use to effectively produce and distribute their product fall into two categories, supply-side management and demand-side management [Nailen 1997].

The first entails activities which the utility directly executes to control its costs. This can include improved operation and design of generation and transmission capabilities. The efficiencies of generating facilities could also be increased or a less expensive fuel source used. The end result is to produce current and future energy needs at the lowest cost for the supplier.

The converse strategy is to reduce the demand for electricity and thus postpone the development of future generating sources. Demand side management seeks to increase the efficiency of energy usage by the consumer and thus reduce the increased need of more expensive generating capacity. These activities are usually sponsored by the utility but can be carried out by any energy-conscious organization interested in conservation. Possible electricity saving options include efficient lighting, more extensive heating and cooling controls, improved building materials, adjustable speed drives, and energy efficient motors. Since the 1970 energy crisis better consumer usage has been a goal, not only of the utility industry, but of many other concerned parties as well. The following is a partial list of such entities [Nailen 1997]:

Alternative Energy Corporation
American Council for an Energy-Efficient Economy
American Public Power Association
American Society of Heating, Refrigeration, & Air Conditioning Engineers
Association of Energy Engineers
Association of Professional Energy Consultants
California Institute for Energy Efficiency
Consortium for Energy Efficiency
Coordinated Canadian Utilities
Department of Energy
Electrical Apparatus Service Association
Electric Power Research Institute
The Electrification Council
Environmental Protection Agency
E Source, Inc.
General Services Administration
Iowa Energy Center
National Electrical Manufacturers Association
National Institute of Standards & Technology
New York State Energy Research & Development Agency
Northwest Power Planning Council
Rocky Mountain Institute
United States Energy Association
Washington State Energy Office
Wisconsin Center for Demand-Side Research
Wisconsin Energy Bureau.

The description of energy efficient motors - the materials and design improvements which reduce energy consumption - necessarily come at a higher price than their standard efficiency counterparts. Utilities have encouraged consumers to buy the more efficient devices with financial incentives for new construction or replacement (whether for a damaged motor or to retrofit a functioning machine). The basic idea is the utility avoids a much larger capital cost (new generating capability) with an upfront outlay to reduce consumer demand. The rebate varies with the motor horsepower but shouldn't exceed the potential savings to be realized by the utility for that particular motor. The rebate usually will swing the motor retrofit decision towards using an energy efficient

machine. However, the actual cost savings is questionable given many different variables beyond the utility's control.

The use of rebates has proved a formidable tool in encouraging the use of energy efficient motors. This is to the satisfaction of environmentalists, those concerned about dependence on foreign oil, and the Environmental Protection Agency. The rebates, however, have proved necessary for the increased use of energy efficient machines. Based on previous penetration forecasts, it was hoped the economic benefits of higher efficiency motors would lead to their use over, and replacement of, standard efficiency motors [Nailen 1997]. This did not happen - mainly because it is usually more cost effective, in the short term, to rewind and repair a motor rather than replace it with a more efficient, and expensive, machine. This is even more true when a functioning machine is retrofitted to reduce energy consumption. Also, new equipment expenses come from capital investment money which can be harder to obtain than repair money, which comes out of the operations and maintenance budget and requires less approval to spend.

Due to the slow penetration of energy efficient machines within industry many regulators began requiring incentives to increase their use. The influence of rebates have resulted in a steady increase of incentive expenditures (Table 6.3).

	Demand Side Management Expenditures, billions of dollars
1989	0.8
1990	1.2
1991	1.7
1992	2.2
1993	2.8
1997	3.9

Table 6.3: Utility Rebate Expenditure Increases for 1989 - 1997 [Nailen 1997].

As a result of incentives, or the desired efficiency improvements, the market penetration has increased. In 1994, approximately 40 percent of the motors in the market were energy efficient [Nailen 1997]. It is difficult to ascertain accurately the impact of rebates on the motor population and the utility's bottom line.

The "avoided cost" an incentive realizes can be substantial. For generating plants, the expense might range from $1,000 to $3,000 a kilowatt for increased capacity. After the costs of administering a rebate program are considered, it typically cost $300 - $400 per kilowatt reduction in energy demand for the use of energy efficient motors [Nailen 1997]. Slowing new demand can result in a substantial savings rather than the gradual increase of generating capacity to meet the demand.

However, these savings may not always be realized. It can be difficult to quantify the energy savings from a new machine which in turn must justify a rebate. If the savings are not correctly calculated then the rebate may never be recovered. Another factor is the

newly effective EPACT legislation which requires the use of energy efficient motors in all new applications [Campbell 1997]. As the prevalence of standard efficiency machines declines, there will be less incentive for utilities to encourage the use of energy efficient motors. It would take a new generation of energy efficient devices to again make rebates a driving market force.

Rebates can make quite a difference in the payback period for retrofitted motors. The following example [Pillay 1997] shows what happens when an oversized standard efficiency motor is replaced by a smaller, energy efficient motor. This methodology takes into account what percent loading of the machine will be economically viable.

First, the current motor output is computed as

$$\frac{x * y}{100} \text{ hp}$$

where the motor size is x horsepower and it is loaded at y percent. If the percent efficiency of the motor at y percent loading is N_1 then the input power, or demand, is

$$\frac{x * y * 0.746}{100 * (N_1/100)} \text{ kW.}$$

The demand charge for the motor over a year is

$$\frac{x * y * 0.746 * 12 * w}{N_1} \text{ \$}$$

where w is the monthly demand charge in $/kW - month. Demand charges reflect the investment required by the electric utility to serve the customer's maximum rate of consumption (demand). The investment covers all fixed utility costs such as capital invest-

ments depreciated over the estimated equipment life as well as other predictable costs such as interest and insurance [IEEE Std 241-1990, p 155].

The energy charge is the second component of a monthly utility bill and is computed as the product of the input power and the number of hours of operation to give the kWhr. This is then multiplied by the energy charge in $/kWhr to give the energy charge which finally becomes

$$\frac{x * y * 0.746 * s * t}{N_1} \ \$$$

where s=$/kWhr and t is the number of hours of operation in a year at the y percent loading.

The new, smaller horsepower motor will operate in a similar manner. The output power,

$$x * y * 0.746,$$

will be the same for the larger horsepower motor but will have an improved efficiency N_2 at its y percent loading. Therefore, x * y * 0.746 is considered the same for both motors even though the individual horsepower and loading are different. The required input power will then be

$$\frac{x * y * 0.746}{N_2} \ \text{kW.}$$

The demand charge will equal

$$\frac{x * y * 0.746 * 12 * w}{N_2} \ \$$$

and the energy charge is

$$\frac{x * y * 0.746 * s * t}{N_2} \ \$.$$

The improved efficiency will be offset by up-front costs related to the motor change-out. These will include the motor cost \$k, the labor cost \$l, the cost of additional gear which can include a new coupling \$g, the new heater element \$h, and the new base plate \$b. These additional costs k + l + g + h + b must be recovered in an acceptable payback time by the energy and demand savings given by:

$$\frac{k + l + g + h + b}{A\ \$/yr + B\ \$/yr - C\ \$/yr - D\ \$/yr} \quad \text{years}$$

where

$$A = x * y * \frac{0.746 * 12 * w}{N_1}$$

$$B = x * y * \frac{0.746 * s * t}{N_1}$$

$$C = x * y * \frac{0.746 * 12 * w}{N_2}$$

$$A = x * y * \frac{0.746 * s * t}{N_2}$$

which reduces to

$$\frac{k + l + g + h + b}{\frac{1}{N_1} - \frac{1}{N_2}} \quad * \quad \frac{k + l + g + h + b}{(x * y * 0.00746) * ((12 * w) + s + t)} \quad = \text{p years.}(6.4)$$

From (6.4) it is apparent the smaller the up-front cost factors k + l + g + h + b then the shorter the payback period. Also, the higher the output power, x * y * 0.746, the smaller the payback period. Lastly, the greater the efficiency improvement the lower the payback period. The payback period also goes down with reduced energy and demand charges as well.

payback period. The payback period also goes down with reduced energy and demand charges as well.

A straightforward numerical substitution [Pillay 1997] shows the impact of different factors on the payback period. Suppose:

w = \$14.70	g = \$115
t = 8,000 hours	h = \$20
s = 0.027 \$/kWhr	b = \$92
x = 100 hp	l = \$363
y = 50% = 0.5.	

With a horsepower standard efficiency motor at 50 percent loading, N_1 is 88.5 percent. It is replaced with a 60 horsepower energy efficient motor at 83 percent loading whose N_2 is 94.4 percent. The new motor costs \$1,598.00 and the total replacement cost is \$2,188.00. From (6.4) the payback period is 1.76 years.

Changes in motor efficiency and loading will result in a corresponding larger or smaller payback period. A reduction in the cost basis, such as a utility rebate, will also bring down the payback period. If the utility offers a \$300 rebate on the new motor cost then the payback period decreases to 1.52 years. With the right combination of variables, a rebate can make the difference in deciding whether to replace or repair a motor.

Some examples of rebate values come from the Iowa Electric utility [Jackson 1994] which uses the NEMA MG1 Table 12 motor efficiency values. Some rebate values from their schedule include:

1 hp at 82.5% efficiency qualifies for \$25 rebate
30 hp at 92.5% efficiency qualifies for \$200 rebate
200 hp at 95.0% efficiency qualifies for \$1,000 rebate.

To qualify for these rebates, Iowa Electric requires approval of an application from the user. This includes proof of purchase and the operating efficiency for all motors being considered. The utility verifies these are all installed and then provides a cash rebate. The owner agrees to allow any motor to be metered for efficiency within the next eighteen months. This process, however, has become less ideal. The rebates involve immediate out of pocket expenses which are supposed to save future, much larger generation and construction costs [Campbell 1997]. These expenses will not be needed for many years though, and could never be realized if demand does not rise as expected or generation comes from other sources. This is one of several factors which are leading to the decline of monetary rebates.

The determination of energy savings for the purposes of rebate justification is dependent on assumptions which can skew their proper use. Operating hours are an important factor. The previous example [Pillay 1997] used continuous operation of a motor for 8,000 hours, 24-hours a day, seven days a week. This is usually not the case, however. Plant shutdowns and regular maintenance will reduce the operating hours and the chance to recover the additional costs for an energy efficient motor. A figure of 4,000 to 5,000 hours is more typical for annual operation [Nailen 1997]. The actual motor efficiency is also difficult to determine. The efficiency rating in the catalog or literature (which is usually used in the rebate calculation) can differ from the nameplate value. The same goes for the nameplate value, which is the nominal value from a sampling of motors, and the actual motor's efficiency. The operating conditions may also be different for where the motor is actually used, leading to a change in efficiency. It is also important to know the efficiency of a retrofit candidate already in use. This can help determine if a

rebate will make replacement worthwhile. However, it is almost impossible to accurately determine efficiency while the motor is in use. The current methods practical for jobsite use are all seriously flawed and depend on one or more of the following erroneous assumptions [Nailen 1997]:

1. Full-load rpm marked on a motor nameplate is accurate.
2. The value of stray load loss can be accurately assumed.
3. Subjected to the same degree of either undervoltage or phase imbalance, the existing and the new energy efficient replacement will both exhibit the same variations in performance.
4. Both existing and new motors will drive the same load at the same speed so that the driven machine power requirements will be the same.
5. Load current varies linearly with shaft horsepower.

The inaccuracies are not great but an error band of 1 - 4 percent can blur the line between standard and energy efficient machines at the larger horsepowers. Even a rewind can produce an efficiency change of 1 - 2 percent [Nailen 1997] which would be missed by conventional testing methods.

There are also problems with the rebate concept in general. It can be very difficult for a utility to know what to offer as a rebate. Neither motor manufacturers or distributors are willing to share what their costs are [Nailen 1997]. Therefore, it is possible the utility may offer a rebate for a certain motor which exceeds the premium between the standard and energy efficient versions. The only reference the utility has is market research which may not reflect other discounts or benefits a user could get from a manufacturer. Thus, the utility may pay a rebate larger than the premium, resulting in a windfall for the user.

efit of using an energy efficient motor. There is really no way to stop this. One utility started a "buyback" program to keep lesser efficient motors out of use. In addition to paying the user a rebate to cover the premium on an energy efficient motor, the utility also paid the repair shop to take in the failed motor and destroy it [Nailen 1997]. This program destroyed several hundred motors before considered no longer necessary.

The economics of rebates, who ends up bearing the final cost, has also brought some doubt to the practice. Some of the issues include [Nailen 1997]:

1. Why should utility customers A, B, and C subsidize the energy savings realized by customer D?

2. In a supposedly free-market economy, artificial market stimulants such as price supports are neither just nor justifiable. Let the product sell on its merits or not at all.

3. Should not the utility stockholders foot the upfront bill to achieve a postponement in generating capacity investment?

4. The motor replaced by higher efficiency, subsidized units will only end up somewhere else on the utility grid, so the net gain in energy efficiency will be less than expected.

5. Paying owners to use an energy efficient device reduces income to the utility from lost revenue and rebate payouts.

6. The 1992 Energy Policy Act will mandate the use of energy efficient motors anyway.

These questions and the reliance on inaccurate assumptions have begun to witness a decline in the use of motor rebates. This has also been accompanied by limiting factors permeating the industry. Following are some of the changes which have taken place [Nailen 1997]:

1. Market penetration of energy efficient machines has increased and rebates no longer seem necessary to encourage their use.

permeating the industry. Following are some of the changes which have taken place [Nailen 1997]:

1. Market penetration of energy efficient machines has increased and rebates no longer seem necessary to encourage their use.

2. Avoiding future generation costs is no longer a great incentive for utilities to allow rebates. Most base-load generating capacity appears to be sufficient into the near future. Natural gas turbine power at $300 a kilowatt is available to meet short-term peak needs.

3. Some concern has arisen over paying rebates to those who would use energy efficient motors regardless (namely the continuous process industries). These excess rebate payments have been estimated between 10 and 40 percent of total rebates.

4. EPACT legislation will dictate higher efficiency for motors. Any future rebates would have to be based on values exceeding the current NEMA ratings.

5. The deregulation of the utility industry will require newly defined organizations to compete on a revenue basis rather than having their costs and fees dictated by a regulatory agency. This means to stay in business and maintain market share they must reduce costs and rebates are vulnerable.

Rebates may have seen their day and will continue to decline in use. The opportunities for customers to conserve energy are still there but may not be subsidized by utility payments. There is also the possibility newer, more efficient machines will encourage rebates in the future. Regardless, it is still in the customer's best interest to improve the efficiency of their process, whether through better motors or throughout the entire system. Utilities and consultants can aid in process improvements, which have much more potential as discussed in Section 2.1. Electric motors, already highly efficient energy transfer devices, have become less a factor in system losses. This has paved the way for improvements throughout a motor-driven process.

CHAPTER 7

EFFICIENCY IMPROVEMENT ALTERNATIVES

Improving the efficiency of an entire process begins by making the correct motor choice and continues with proper application of the machine and optimizing the energy transfer to the driven process. The motor's performance is greatly improved by considering such things as the supply voltage, phase balance, harmonics, motor sizing, and power factor. Also, adjustable speed drives and appropriate drive belts help transfer the motor energy as smoothly as possible.

Evaluating the entire drive system provides a greater return on the time and money invested to improve the process cost savings. It also can improve conditions aggravated by energy efficient motor characteristics. System evaluation is time well spent and, if absent, may cancel any gains provided by energy efficient devices.

7.1. Adjustable Speed Drives

Solid state electronic adjustable speed drives (ASD) have been available since the early 1970's and mechanical versions using relays were used even earlier [Nadel et al 1992, pg 109]. They have not come in to common use until recently with the advances in power electronic devices. Before, they were very costly and somewhat unreliable. Rather than using mechanical pulleys or hydraulic couplings to transfer a portion of the driveshaft

energy to an output shaft, the ASD changes the driveshaft speed intrinsically. The most commonly used is inverter based - a rectifier converts 3-phase ac input to dc, the dc is filtered to smooth the rectified voltage ripple, and then an inverter converts the dc to an adjustable frequency, adjustable voltage ac waveform. The speed of the motor then changes in relation to the supply frequency.

Inverter ASDs come in three types - voltage source inverter (VSI), pulse width modulation (PWM), and current source inverter (CSI). Each has their own advantages and disadvantages and best use in the marketplace.

The VSI builds a sine wave by combining dc square waves of varying lengths and constant magnitude to build a staircase version of the sinusoidal waveform. The losses are low because little switching action occurs and the voltage magnitude is easily changed by increasing or decreasing the number of square wave "steps". The frequency changes with the length of the square wave components. VSIs are used in low to medium power applications, typically up to several hundred horsepower, and can operate several motors at once [Nadel et al 1992, p. 112].

PWM inverters synthesize a sinusoid by varying the energy released from the dc square wave into short pulses of differing duration. The switching speed controls the frequency of the output sine wave and the motor speed. PWMs provide good efficiency at low speed and high speed ranges so their use has increased. The PWM's versatility has led to it being the predominant inverter of choice.

The CSI does the same thing for current as the VSI does for voltage. They, however, have regeneration capabilities which convert the energy of a braking motor back into

usable electricity. They are used for large drives above 200 horsepower because of their simplicity, reliability, and lower cost [Nadel et al 1992, p. 112].

Electronic ASDs do have some specific concerns. There are switching losses within the rectifier and inverter which reduce the motor efficiency. The losses also heat up the drive and, if it is located in a high temperature environment, additional cooling measures must be taken [Nadel et al 1992, p. 118]. The rapid switching can cause unwanted harmonics and transients. In most drive situations they are not a factor but methods exist to "clean" the input waveform if necessary.

A big opportunity for ASDs are in constant flow devices such as pumps and fans. Normally, the motors are constant speed and the flow of gas or liquid is controlled by throttling. A typical water pumping installation, located on the east coast, supplied water from four 300 horsepower pumps [Lawrie 1993]. The flow was originally controlled by throttling while all four pump motors ran at full speed. The water flow was cut by using valves but the motors continued to run at full power. An ASD was installed on one pump, allowing it to provide any flow needed to adjust the required output, while the other three pumps continued to operate at or near full load.

The total electric bill savings at this installation was over $85,000 per year. The utility also provided a $27,000 rebate. The equipment costs and installation were $54,000 resulting in a four month payback period and an annual $85,000 profit year after year. This large benefit comes from the change-of-speed to energy-cubed relationship of centrifugal pumps and fans. A reduction in motor speed results in a corresponding cubed reduction in motor horsepower [Lawrie 1993].

The basis for this savings begins with comparing the flow rate (Q) to the system pressure difference (ΔP) which is,

ΔP is proportional to Q^2

where:

ΔP is pressure difference in pounds per square inch (psi) or inches or feet of water.
Q is the flow rate in cubic feet per minute (cfm) or gallons per minute (gpm).

This means if the fluid flow doubles, the pressure difference quadruples, a quadratic relationship [Nadel et al 1992, p. 132].

The power required to create a given rate of flow follows from the physics of fluid flow and relates directly to the shaft power supplied by the drive motor to a fan or pump. The power needed is proportional to the product of the pressure difference and the flow rate, or [Nadel et al 1992, p. 133]:

Power is proportional to $\Delta P * Q$.

Using a set of relations for fans and pumps known as the affinity laws takes this further. One law states: for a given fan or pump, installed in a given (unchanging) system, the flow rate is directly proportional to the speed of the fan or pump. This equates to:

Q is proportional to N, where N is speed.

This means if the fan speed is doubled, then the flow rate is also doubled.

Another affinity law states the power required by a fan or pump increases with the cube of its speed, or power is proportional to N^3. If the fan's speed is doubled, the power requirement grows eightfold. This follows directly from the previous relationships where [Nadel et al 1992, p. 133],

Power is proportional to $\Delta P * Q$

and

ΔP is proportional to Q^2

so

Power is proportional to Q^3

but

Q is proportional to N

so

Power is proportional to N^3.

This relationship shows how large energy savings can be realized with a slight reduction in speed for pumps and fans. If the motor speed is reduced 0.8 p.u., then motor horsepower is reduced $0.8^3 = 51$ p.u. It should be noted the affinity laws apply only if all other variables in the system are held constant. This means at zero fluid flow the pressure difference in the system must be zero as well. Typical examples include residential and other ventilation systems that were originally designed to operate at constant air flows, and water circulation systems that do not use pressure controls or other means to create flow-independent pressure differences [Nadel et al 1992, p. 134].

The power - speed cubed relationship can also have an impact on the benefits of energy efficient motors. High efficiency motors tend to have a lower slip and can have up to 1 percent higher speed than its standard efficiency counterpart. This 1 percent speed difference can mean up to a 3 percent increase in energy usage, potentially negating the benefits of an energy efficient motor [Nadel et al 1992, p. 138]. Certain things can be done to reduce the motor's speed such as adjusting the belt or pulley system or using an adjust-

able speed drive but these additional costs should be considered in energy savings calculations.

ASDs are very flexible and provide benefits beyond those involved with pumps and fans. When motors are driving conveyor belts they may or may not be running at full load, depending on what the conveyor is carrying. An ASD could adjust the speed of the motor so it is running at full load, saving otherwise wasted energy [Lawrie 1993]. These drives have many useful applications and can play a role in any motor driven process. The possibilities should be fully explored before implementation to avoid any future problems and the utility or manufacturer should also be consulted to ensure all potential benefits are realized.

7.2. Transfer System

Another way to conserve energy besides regulating the motor's speed is to improve the transfer process between the drive shaft and the driven equipment. This is usually done with drive belts or other mechanical means. If these connections are poorly implemented or misaligned then energy is wasted. Proper turning and maintenance of the system will ensure the maximum amount of energy is transferred to perform useful work.

Most of the energy transfer devices in a motor's drive train - the gears, pulleys, pumps, compressors, fans, and conveyor belts - have inherently high losses regardless. For example, gears and pulleys act as torque multipliers. The drive shaft entering the gear or pulley (high speed shaft) have a lower torque than the shaft on the other side of the gear or pulley (low speed shaft). The losses at these torque transfers are usually much higher than the motor losses. These are cases where the motor efficiency doesn't matter and the

torque transfer junctions should be eliminated if possible or made more efficient [Mecker August 1994].

One area for efficiency improvement are belt drives which compose about one-third of all motor transmission systems [Nadel et al 1992, p. 90]. Most belt losses are caused by flexing and slippage as the belt goes around the pulley. The traditional V-belt has the most flexing losses and, as it ages and the belt wears smooth, slipping increases. Flex can be reduced by a cogged (or toothed) belt drive since less force is required to bend the belt. It provides an ideal retrofit opportunity since the original pulleys are still used. The most efficient belt drive is the synchronous belt. It uses a toothed belt which meshes with a toothed pulley and has low flexing losses and no slippage. It is considerably more expensive than a V-belt or cogged belt but usually has a simple payback within two years. The synchronous belts also last up to four times as long as V-belts [Nadel et al 1992, p. 92].

One recent retrofit examined the efficiency improvement for using synchronous belts [Greenberg 1997]. The motors used were three-phase, ac, single-speed motors not controlled by adjustable speed drives, and generally driving loads of nominally constant flow. Once the motors were selected the belt retrofits involved: selecting belts using manufacturer's selection software, measuring input voltage and power and motor and device speed, installing the belts, and also re-measuring input voltage, power, motor speed, and device speed.

This retrofit only tested five motors and adjusted for a slight drop in speed after the synchronous belts were installed. As noted previously, a small drop in speed results in a cubed decrease in power consumption and so the relative speeds of both applications

would have to be the same to get accurate values. The test did not provide conclusive results, however. The energy savings were positive after the retrofit but once the speed change was factored in they became negative. This one incident showed there is the potential for energy savings with belt improvements but a larger sample or better controlled conditions are needed to provide more accurate results.

Any transmission system can still benefit from proper maintenance and application. Some things to keep in mind are to properly size the motor so it does not run in a constant overload condition. The motor's service factor allows it to run overloaded for short periods of time but not constantly. Proper alignment is also important, without which there will result increased bearing loading and frictional losses. Belt tensioning will help prevent flex losses. Over-lubrication can also be a problem as wasted energy is needed for the bearings to churn excess grease.

In addition, proper environmental conditions for the motor will help extend its useful life. The motor has a cooling fan and fins to provide ventilation. For these features to perform ideally the motor should be kept clean so dust and oil don't interfere with the thermal radiation. Also, excess moisture can lead to insulation degradation and premature motor failure. It helps to keep motor temperature above the dew point, especially if located outdoors. Additionally, space heaters or low voltage windings can remove excess moisture. These are all simple, yet ideal ways to prolong motor life [Jordan 1994].

7.3. Application

The greatest benefit from energy efficient motors are realized when the motors are properly used. Some things mentioned which capitalize on a motor's efficiency are adjustable speed drives and a good energy transmission system. Traditional application

improvements can also result in strong rewards. An important aspect is motor loading. If the load is constantly changing then an adjustable speed drive may be appropriate. However, for constant use motors with no significant load changes proper sizing is needed. Additionally, symmetrical voltage balance across all phases is important for three-phase motors. The voltage magnitude is an additional consideration and should be within $\pm$ 10 percent of the motor nameplate voltage [Mecker September 1994]. The last consideration is power factor. While energy efficient machines do not make a big change in power factor, traditional methods exist to improve it when additional utility charges become a problem.

7.3.1. Loading

A motor must overcome resistance from various sources when rotating and, for the motor to be efficient, most of this force should be directed towards the load which needs to be moved and not to losses. Therefore, load is the label given to the connected components that cause resistance to the rotational portion of the motor's shaft. These connected components are the primary load, such as a machine, pump, or fan as well as gears, pulleys, and other mechanical moving parts [Mecker August 1994].

One straightforward consideration for load is the amount of time a motor needs to run. If a conveyor only carries a load for a portion of the day then it might be more economical to turn off the motor when it is not needed. A low load is usually when a motor has its poorest efficiency as well. As a result it may be better to downsize a motor than to run it poorly loaded.

Conversely, a motor's best performance doesn't occur at 100 percent loading but usually around 75 percent [Bonnett 1994b]. Typical motor efficiencies are shown in the

following table for different horsepower. In most cases the full load efficiency is equal to or less than the 3/4 load efficiency.

HP	1/2 Load	3/4 Load	Full Load
1	79.6	82.3	82.5
2	80.7	83.6	84.0
5	88.5	88.7	89.5
10	91.0	90.7	87.5
15	91.3	92.0	89.5
20	92.6	92.7	91.7
25	92.9	93.2	93.0
30	93.3	93.6	93.6
40	94.7	94.5	93.6
50	95.1	94.8	94.1
100	95.2	95.4	95.0
200	96.4	96.7	96.5

Table 7.1: Typical Motor Energy Efficiency in Percent [Mecker August 1994].

Other testing has shown motor efficiency to continue to drop off as loading goes below 50 percent [Nadel et al 1992, p. 75]. Therefore, as a general rule, a motor should be sized to run at 50 percent or more of its rated load most of the time. In some cases it may be necessary to oversize a motor to meet momentary peak demands. If the oversizing extends beyond 50 percent of the standard load then another option is to use a more suitably sized motor with a higher service factor to handle short-term demands [Nadel et al 1992, p. 73].

7.3.2. Voltage

The next application consideration is voltage balance and magnitude. Motors are designed to run at rated voltage ± 10 percent and, for three-phase motors, the voltage supply is symmetrical [Nadel et al 1992, p. 65]. Harmonics, or waveform distortion, can also decrease motor efficiency as was discussed with adjustable speed drives. A symmetrical source voltage is marked by three sinusoidal voltages of equal magnitude and out of phase by 120 degrees. An unbalance occurs when the phases shift or the magnitudes change. Usually the magnitude in one phase changes. Too many single-phase loads not evenly balanced can result in a decrease in voltage magnitude on that phase. Also, different size cables for each phase can lead to varying resistance drops on each phase and a voltage unbalance. This can happen after a partial retrofit which doesn't consider the entire system [Nadel et al 1992, p. 66].

A simple way to describe voltage unbalance is to take the maximum voltage difference between the three phases and the average voltage, divide by the average voltage, and multiply by 100. The formula is [Nadel et al 1992, p. 67]:

$$\text{Voltage unbalance (\%)} = \frac{\text{Maximum difference of the voltages in relation to the average voltage}}{\text{Average voltage}} * 100.$$

A simple example illustrates this expression. If we assign the three phase voltages as follows:

$V_a = 200$ V
$V_b = 210$ V
$V_c = 193$ V
$V_{ave} = 201$ V.

The maximum difference from the average is

$$210\ V - 201\ V = 9\ V$$

and the voltage unbalance is

$$\frac{9}{201} * 100 = 4\%.$$

Voltage magnitude also can change the motor efficiency. A sampling of three different motors at different voltages did show a change in efficiency, generally increasing as the voltage increased [Bonnett 1994b]. A slightly higher voltage means less current is needed to generate the required output power and so there are less stator winding losses. Table 7.2 shows the actual results. ODP and TEFC indicate the type of motor enclosure, Open Drip Proof and Totally Enclosed Fan Cooled, respectively.

	208 Volts	230 Volts	250 Volts
10 hp ODP 1800 rpm	80%	84%	84.5%
50 hp TEFC 1800 rpm	92.5%	94%	94.5%
100 hp ODP 4 Pole	94.5%	95.5%	95.5%

Table 7.2: Efficiency Versus Voltage Variation [Bonnett 1994b].

The 230 volt motor is designed to operate on a 240 volt bus to allow for any voltage drops in the system. In fact, the 230/460 volt motors are the most common [Greenberg 1997]. Another sampling in the petrochemical industry [Pillay 1997] found the full load efficiency of energy efficient motors increased 0.5 - 1 percent for a 10 percent overvoltage but the full efficiency of standard efficiency motors decreased 1 - 4 percentage points. This

means an energy efficiency motor could have an even greater efficiency improvement if a higher voltage is used. This and other observations are spelled out in Table 7.3.

	90% Voltage	110% Voltage	120% Voltage
Starting and Max. Running Torque	Decrease 19%	Increase 21%	Increase 44%
Synchronous Speed	No Change	No Change	No Change
Percent Slip	Increase 23%	Decrease 17%	Decrease 30%
Full Load Speed	Decrease 1-1/2%	Increase 1%	Increase 1-1/2%
Efficiency			
Full Load	Decrease 1-2 Points	Increase 1/2-1 Point	Small Increase
3/4 Load	Practically No Change	Practically No Change	Decrease 1/2-2 Points
1/2 Load	Increase 1-2 Points	Decrease 1-2 Points	Decrease 7-20 Points
Power Factor			
Full Load	Increase 1 Point	Decrease 3 Points	Decrease 5-15 Points
3/4 Load	Increase 2-3 Points	Decrease 4 Points	Decrease 10-30 Points
1/2 Load	Increase 4-5 Points	Decrease 5-6 Points	Decrease 15-40 Points
Full Load Current	Increase 11%	Decrease 7%	Decrease 11%
Starting Current	Decrease 10-12%	Increase 10-12%	Increase 25%
Temperature Rise, Full Load	Increase 23%	Decrease 14%	Decrease 21%
Magnetic Noise, Any Load	Decrease Slightly	Increase Slightly	Noticeable Increase

Table 7.3: Effects of High or Low Voltage on Energy Efficient Induction Motors [Pillay 1997].

7.3.3. Power Factor

The last consideration in motor application is power factor. A high power factor (above 0.9) indicates most of the energy used in a process or by a motor is doing real work. Little energy goes to reactive losses in conductors or to create the rotating magnetic

field in induction motors as compared to the amount of real work done by the motor. A poor power factor is corrected with a capacitor bank, either at the motor or one centrally located.

Little impact has been found on power factor from energy efficient motors. Some design changes, such as increased air gap, will reduce the power factor, but there is not much change. Some designs will increase the power factor by 1 percent and others will show a slight decrease [Nailen 1992]. In any case, correction is easy with capacitors and should not be considered a concern in obtaining higher efficiency. Most large commercial users have an overall high power factor and so won't be impacted by a decrease from some motor loads. Also, if the utility does levy a power factor penalty then it is usually on the larger customers who have more opportunities to utilize some correction [Cowern 1982].

7.4. Motor Management Program

A final, low-tech, method to achieve improved system performance is the implementation of a motor management program. To accurately assess economic factors and make informed decisions about motor replacement or repair it is important to have a good understanding of the existing system. Some facts worth knowing are [Brethauer et al 1994]:

1. Motor repair and operating history.
2. Quality and cost of past repairs.
3. Efficiency differences between repaired and new motors.

Most of the time little of this information is kept because when a motor does fail it is repaired as quickly as possible. Also, an old motor, about which nothing is known, could be reintroduced into the system as a replacement. This leads to unknown efficiency values and maybe even improper loading or voltage application. A good database on

existing motors in service or backstock can reduce these problems and even lead to preventive maintenance and reduction of future failures.

An even more detailed inventory could help identify which motors would be suited for retrofit with an energy efficient motor. Some items for consideration are [Hirzel 1992]:

1. General Condition: Damage to the enclosure or insulation could be a sign of multiple rewinds (and multiple failures).

2. Age: Older motors are prone to fail and often have lower efficiency than those built in recent years.

3. Annual Hours of Operation: Motors running constantly are the best candidates for retrofit with an energy efficient motor. Motors used for shorter periods should be considered if electric rates are high.

4. Load Profile: Motors running at or near full load are the best candidates for energy savings in a retrofit. Underloaded motors can also realize savings when retrofitted with a properly sized motor.

5. Operating Speed: The biggest gains in efficiency are obtained in motors operating between 1,200 and 3,600 rpm.

6. Application: Motors in constant load applications are better candidates for retrofit than those with varying load requirements.

7. Standard or Special Design: Specialized motors are usually not good candidates for retrofit. They should be fitted with mounting adaptors first to convert the drive system to a standard motor configuration.

One motor management program which has seen widespread use is the Motor Challenge MotorMaster+ software. It is sponsored by the U.S. Department of Energy's Motor Challenge program with development support provided by the Washington State University Cooperative Extension Energy Program in conjunction with the Bonneville Power Administration. The Motor Challenge program targets energy conservation opportunities of AC motors and adjustable speed drives with emphasis on demand side management [Bonnett

1995]. One of its main products has been the MotorMaster+ software decision-making tool.

MotorMaster+ first appeared in 1992 and is a software program that contains an unbiased database, updated yearly, of over 13,800 National Electric Manufacturers Association Design B three-phase induction motors, ranging from 1 to 600 horsepower. All motors are tested under IEEE 112, Method B to guarantee consistency and other information is provided by the manufacturer. The database even corrects for an energy efficient motor's lower slip (the motor runs at a slightly higher speed than a standard efficiency motor of the same horsepower). As discussed in 7.1., the power expenditure increases with the cube of speed and the software considers this effect when analyzing savings for replacing motors in applications with centrifugal loads such as motors and pumps [Gilbert et al 1997].

MotorMaster+ provides industrial users with the following four capabilities to meet their motor system requirements [Gilbert et al 1997]. The first is inventory management. It allows the user to develop and maintain an inventory of motors and associated loads within their facility. Typical data tracked includes motor nameplate information; process and location codes; load type, operating hours, and working environment descriptions; and measured data such as voltage, amperage, power factor, and speed at the load point.

The second feature is a catalog which lets users obtain information on motor prices, efficiency, power factor, performance, or quality to help select a motor that best fits their needs.

The third, and most powerful, is an analysis tool. Users can compare a standard or rewound motor with a new energy efficient motor, calculating annual energy and demand savings, operating costs and simple payback period. It can also determine the cost effectiveness of replacing a failed or operable motor with an energy efficient unit. This even includes life-cycle analysis and the ability to compute the after-tax return on investment for an energy efficient motor.

Lastly, is a tool to help with rebates. The software indicates which motors qualify for a utility rebate and can print out the actual rebate forms for some utilities.

The MotorMaster+ software is a quite comprehensive and dynamic tool. Upgrades are planned for the future such as increasing the types of NEMA motors listed. Also the reports menu will be expanded to include formats suited for plant management, providing energy savings summaries by facility. The software is used by people throughout the motor production, distribution, end-user, and repair network to capture energy savings associated with motors and the equipment they run. It is an excellent tool to manage a large number of machines and processes which must be compared against an ever increasing number of energy efficient products.

CHAPTER 8

CASE STUDIES

The benefits of energy efficient motors have been touched upon in the preceding chapters and industry has taken these cost reducing measures into consideration. There have been several articles about plants reducing their electric bill with energy efficient motor retrofits. As explained, most of these plants are in the continuous process industries. Paper and pulp processing, sawmills, and petrochemical plants - whose electric motors run constantly - have the best opportunity to obtain a quick payback on the premium for an energy efficient motor. After the initial costs are recovered, energy savings quickly accrue. The Motor Challenge program has also encouraged efficient motor use by sponsoring "Showcase" projects which high-light a company's efforts at reducing energy costs.

8.1. Industry Examples

a. One realization of electric cost reduction occurred at the Stone Container Co., York, Pennsylvania [Lawrie March 1994]. From 1989 to 1994, this large paper/cardboard-processing plant saved over $500,000 on its electric bills primarily by replacing standard efficiency motors with energy efficient versions. The plant used about 600 induction

motors in its various processes and had retrofitted approximately 300 of them. Projected savings for 1994 was approximately $200,000.

The plant manager decided which motors to replace, whether by failure or use, and then enlisted the help of a local electrical apparatus service firm to prepare an economic analysis. This showed how long it would take an energy efficient motor to "earn" back it's premium cost. The plant manager also appreciated the sturdier construction of EEMs (heavy duty bearings and insulation) and the less maintenance required.

b. Another heavy industrial plant, a steel processing mill, realized savings by using energy efficient motors for its hydraulic pumps [Mecker October 1994]. 31 motors were used in the hydraulics area. Nineteen 100 horsepower motors supplied oil to hydraulic cylinders and high pressure processes. The other twelve 15 horsepower motors drove a roll-change system. A cost analysis of this system using energy efficient motors showed an annual energy savings of $10,254, resulting in a simple payback of 3 years and 4 months.

The plant also examined motors moving the steel through the milling process. Typically, dc motors are used because of the precise speed control required to coordinate the steel movement through different presses. However, with ASDs, the plant manager could use more reliable induction motors instead and realize an energy savings as well as reduce maintenance costs. 170 of these 7 horsepower motors are used and must withstand very high temperatures, an extremely wet environment, dust, and grease. In this environment reliability becomes very important.

8.2. Motor Challenge Showcase Demonstration Projects

The Motor Challenge program has cataloged some impressive Showcase Demonstration Projects as well. These projects target electric motor-driven system efficiency and productivity opportunities in specific industrial applications. They show that efficiency potential can be realized in a cost effective manner and encourage replication at other facilities [DOE September 1996]. Four examples follow.

a. A study undertaken at Building 123 on the headquarters campus of Minnesota Mining and Manufacturing reduced electricity use by 41 percent with subsequent cost savings of $77,554 per year [DOE September 1996]. These benefits were the result of four key upgrades:

1. A direct digital control system cut power to air supply exhaust fans when not in use. An adjustable speed drive was also used to control the speed of the supply makeup air fan motor so it did not constantly run at full speed.

2. Five reheat water supply pumps were retrofitted with energy efficient motors. Also, adjustable speed drives were installed so the pumps were not on constantly with unneeded flow diverted through bypass valves.

3. Air supply fans had been running constantly and the flow controlled with dampers. Again energy efficient motors were used and controlled by adjustable speed drives.

4. Motors running over 6,000 hours per year were evaluated and 28 retrofitted with energy efficient motors.

These four improvements not only resulted in reduced electricity costs but required less steamed and chilled water in the two systems which heated or cooled ambient air before supplying it to the occupied space.

b. Another improvement effort took place at a sewage pump station [DOE December 1997]. With the help of an electrical apparatus consultant, the town of Trumbull, Con-

necticut, altered the existing pump system by adding a smaller pump and modifying the existing control system. The smaller pump handled the same flow as the original pumps during non-peak periods but ran for a longer period of time. The smaller flow also reduced friction and shock losses in the piping system, which lowered the required head and energy consumption.

The total effort reduced annual electricity consumption by almost 44 percent, saving over $2,600 per year. The project cost $12,000 and had a simple payback of four and a half years. The experience from this project could be used at Trumbull's other pump stations and at similar facilities throughout the country.

c. Adjustable speed drives played a key role in reducing energy costs at a recycling and solid waste-to-energy plant in Long Beach, California [DOE February 1998]. The recovery facility seeks to use mass burn technology in reducing the amount of solid waste which must be sent to landfill. The heat generated is used to produce electricity to run the plant with excess sold to the local utility. Three waste-burning boilers provide steam to run the generator.

Each boiler has a 500 horsepower induced draft fan on the boiler's exhaust side, providing negative air flow to draw the exhaust gas through a pollution control system. The fans were originally controlled by throttling the flow with dampers. This was inefficient because, on average, the damper was 47 percent open while the fan was running constantly. Installation of adjustable speed drives on the fan motors allowed the air flow to be controlled by the fan speed instead. The annual electrical energy consumption of the three fan motors decreased 34 percent, realizing an annual cost savings of $329,508.

d. A final Showcase Demonstration project took place at a plating facility in Burlington, Vermont [DOE August 1996]. The plant used a constant air flow hood and duct system to remove hazardous vapors near plating tanks. The ventilation system ran constantly regardless if a particular tank was inactive. After studying the appropriate ventilation standards as defined by the Occupational Safety and Health Administration, adjustable speed drives were used to provide the required fan speed. This allowed fan speed to be greatly reduced during idle times. An energy management system was installed to control the drives as well as provide monitoring and coordination with other building functions. The reduction in energy consumption provided annual energy savings of $68,000 and a simple payback of one and a half years.

These case studies show how energy efficient motors and other energy efficient technologies are readily implemented. The benefits are quickly seen and payback of the investment cost is usually short. Additionally, examination of the entire motor driven process shows a reduction in other utility costs (steam and chilled water) as well as increased reliability and reduced maintenance. The benefits are many and more examples are available every day.

CHAPTER 9

CONCLUSIONS

Throughout the preceding chapters the EEM characteristics were defined and explored. This has included problems which may result from their use and appropriate solutions. In most cases the EEM is just as reliable, or more so, than any motor it will replace. It provides the motor user with a straightforward, cost-cutting solution in almost any application. In fact, due to lower losses, the possibility exists to increase the motor's performance and life expectancy [Bonnett 1997]. Additional technologies such as adjustable speed drives provide the control needed to limit unneeded motor use. They also reduce an EEM's speed when driving a centrifugal load to maintain the machine's efficiency [Pillay 1997].

The EEM is more present in industry due to economic considerations and, as the 1992 EPACT takes effect, due to policy implementation as well. The legislation mandates new efficiency standards, testing, and labeling requirements for NEMA motors. The Act does not cover special purpose motors but most general purpose applications will be affected eventually. The testing requirement standardizes how efficiency variables are measured and the resulting efficiency calculated. The method uses the widely accepted IEEE 112-B criteria which takes a conservative stance to stray load losses.

Lastly, the new EPACT standards set a new baseline for electric motors and could someday spur a new generation of EEMs. These more stringent standards also affect the economics of replacement decisions. They have made most utility rebates obsolete and so an owner must rely solely on the energy savings.

Energy efficient motors do not use new technology explicitly. They utilize advances in material science, electronics, and computer science. Improved motor materials reduce hysteresis loss in the core. New computer assisted design techniques allow a better understanding of where losses occur and the best combination of design parameters to reduce these losses. These gains are made with no reduction in motor performance and, typically, the motor's reliability improves.

An important issue is the high inrush current energy efficient motors draw at starting. This can nuisance trip protective devices. The starting current is usually asymmetrical and the magnitude can theoretically double as a result of the motor's increased X/R ratio. Since EEMs have lower winding resistances their X/R ratio should be larger. However, what also must be considered is the overall improvement in motor design for standard motors. Testing has shown little difference between standard and energy efficient X/R ratios. The increased robustness of motor design may be leading to a higher asymmetrical starting current in general. In either case the situation can be solved with an adjustable inverse time circuit breaker. This analysis demonstrated EEMs are still effective when properly applied and controlled. Nuisance tripping is an issue but not insurmountable.

Other aspects of the energy efficient induction motor set the stage for economic analysis of various replacement scenarios. The major causes of motor failure were intro-

duced, focusing on the breakdown of winding insulation. When a motor fails it is typically repaired (rewound). This is usually the fastest and the lowest initial cost solution. However, motor rewinds are not without consequences and there is usually a slight efficiency drop. This sets the basis for determining the best economic solution in the use of efficient motors in repair vs. replace scenarios as well as initial use in a new application. Most design decisions must be economically viable and tools for analyzing different options are critical. In general, when operating hours are high and there is a notable efficiency improvement, the EEM comes out ahead. This does not even consider the technology improvements in newer motors which lengthen service life and reliability.

Utility rebates are another factor which have played a role in making the choice between energy efficient and standard motors. In the early 1990's, utilities began encouraging EEM use by offering to cover the EEM premium. With this rebate there was usually little question that the EEM was the best choice. However, as EPACT begins to take hold, there is less incentive for utilities to perform this function since EEMs are required in new applications regardless. The rebate is a great opportunity but will probably become less available until the next generation of EEMs.

Energy efficient motors don't operate in a vacuum, however, and great rewards are realized when examining the entire motor-driven process. Proper maintenance and installation provides the first step in ensuring reduced energy use. Continuous monitoring of the system is also needed to keep the supply voltage at its desired level and reduce overvoltage or voltage balance problems.

The energy transfer system is another large source of loss. Proper belt tensioning, gear lubrication, etc., will reduce these losses. Adjustable speed drives probably provide

the greatest system benefit through their ability to limit motor speed when demand is reduced. This is especially true for centrifugal loads which draw power as the cube of motor speed.

Understanding each aspect of energy efficient motor application can provide plant and motor operators with large cost reductions. This benefits not only the owner but the utility as well, allowing it to postpone future demand generating capability. Finally, it rewards the general public with lower overall costs and reduced emissions from fossil-fuel burning generation facilities. Continued improvement in these areas will help "raise the bar" for energy consumption reduction. Future energy efficient motor standards will recognize this trend. NEMA has developed standards for a Design E motor which, among other things, has an energy efficient standard higher than the current EPACT requirement [Kilburn and Daugherty 1997]. This paves the way for a new generation of energy efficient motors.

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